

# HERSCHEL CRYOGENIC SYSTEM AND STATUS OF (SOME) EUROPEAN CRYOCOOLER DEVELOPMENTS



Lionel DUBAND

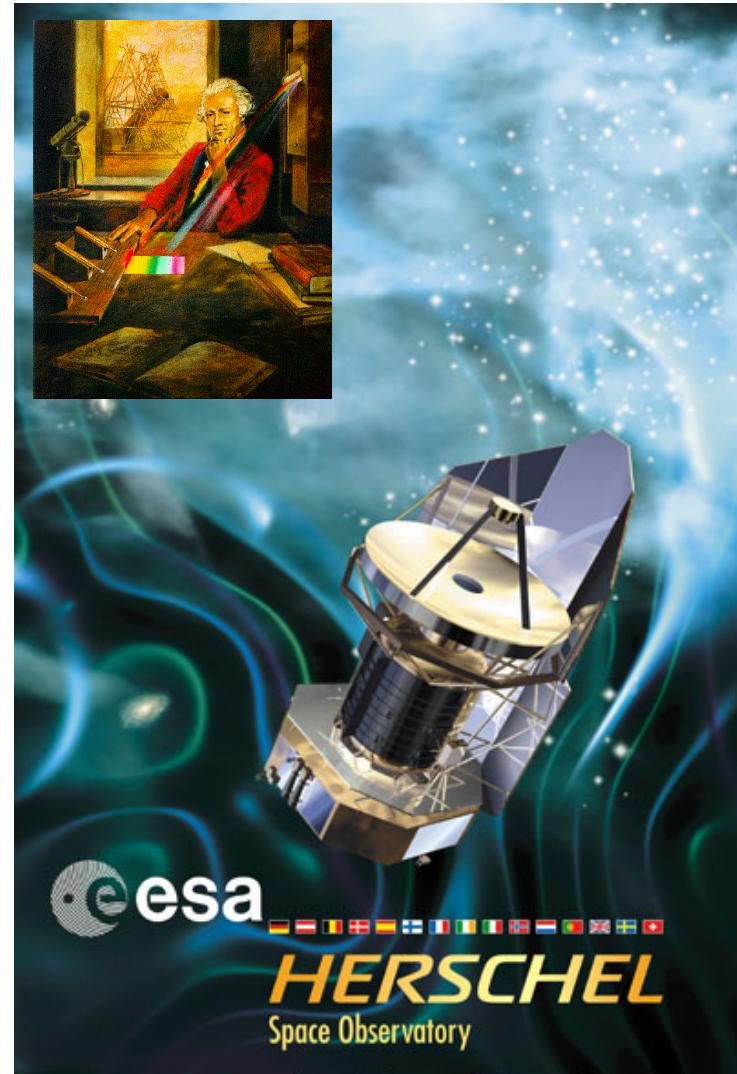
**Service des Basses Températures CEA-SBT  
GRENOBLE - FRANCE**

(CEA/DSM/DRFMC/SBT)

- **ESA cornerstone observatory mission**
- **Launch : Feb. 2007 (Carrier Ariane 5 - L2 orbit)**
- **First space facility to completely cover this part of the far infrared and submillimetre (57-670  $\mu$ m) range**
  - large (3.5 m), low emissivity (~ 4%), passively cooled (< 90 K) telescope
  - 3 cryogenically cooled focal plane science instruments, 3 years ops lifetime
  - total absence of (residual) atmospheric absorption - full spectral access - and emission
    - low and stable background

## HERSCHEL MAIN SCIENTIFIC OBJECTIVES

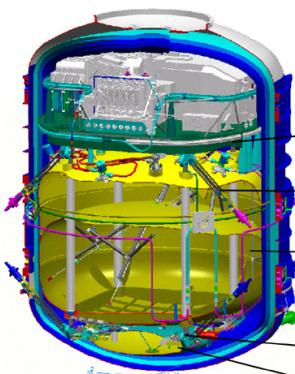
- **Formation and evolution of galaxies**
- **Formation of stars**
- **Cometary, planetary and satellite atmospheres**



# INSTRUMENTS : 3 POWERFULL EYES

- **PACS (57 - 210  $\mu\text{m}$ )**

- Imaging photometer
- Grating spectrometer



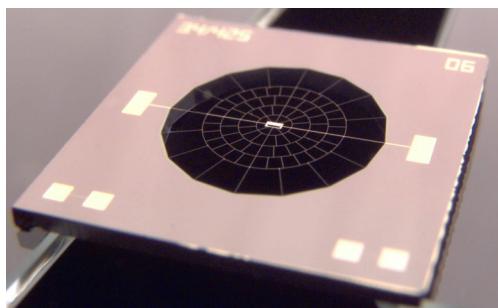
- **SPIRE (200 - 670  $\mu\text{m}$ )**

- Imaging photometer
- Fourier transform spectrometer

- **HIFI (157- 212  $\mu\text{m}$  and 240 - 625  $\mu\text{m}$ )**

- Heterodyne spectrometer

**BOLOMETRIC DETECTORS  
COOLED @ 300 mK**

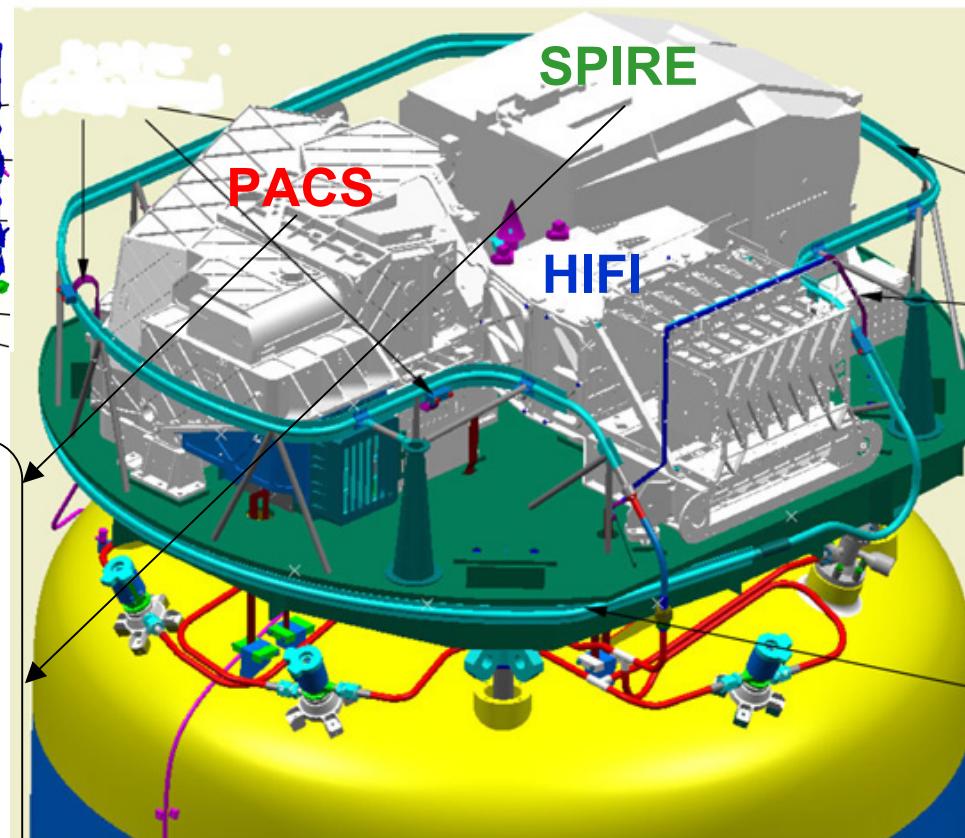
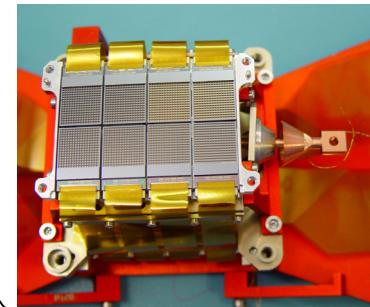


**SPIRE :** Spider Web  
Bolometer  
(Caltech/JPL)  
Fast response

**PACS :** Fielded Array

Bolometer  
(LETI Grenoble)

Silicon micromachining (collective  
manufacture)  
CCD like arrangement



*Note : Specific thermal architecture*

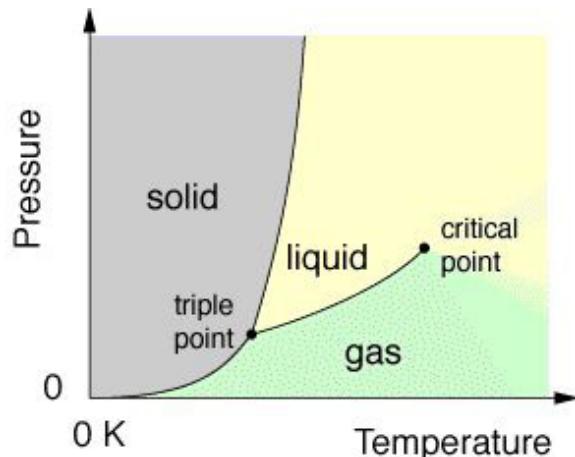
- Cryostat at level 0 ( $\approx 1.7 \text{ K}$ )
- Instruments at level 1 (0) ( $\approx 4-5 \text{ K}$ )

**Design and performance driver !**

# SELECTED TECHNIQUE : EVAPORATIVE COOLING

COOLING PROCESS → ENTROPY REDUCING PROCESS

*Cooler = "entropy-squeezer"  
(Simon)*

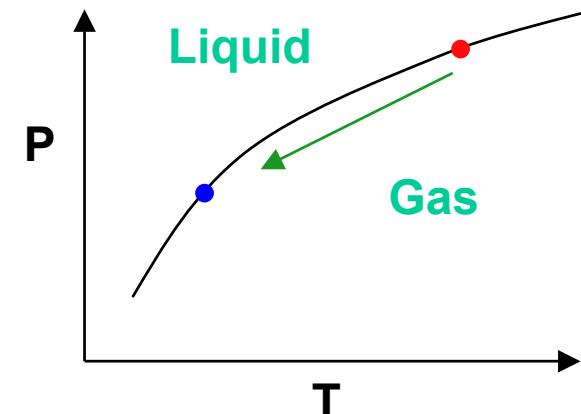
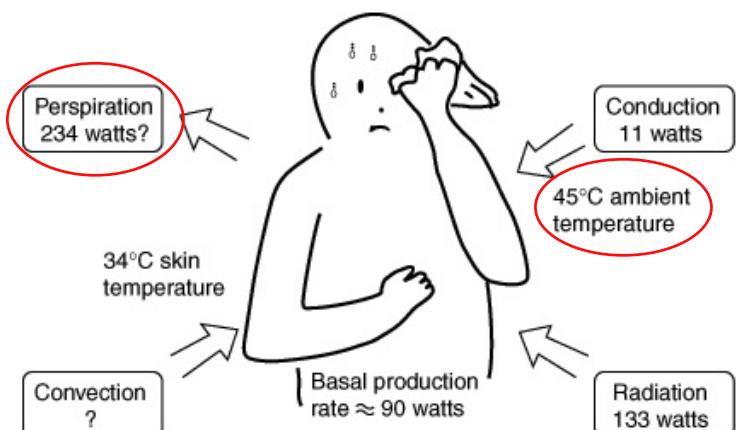


Evaporation ?

$$S_{\text{vapor}} > S_{\text{liquid}}$$

"Flowing" atoms  
from liquid to gas

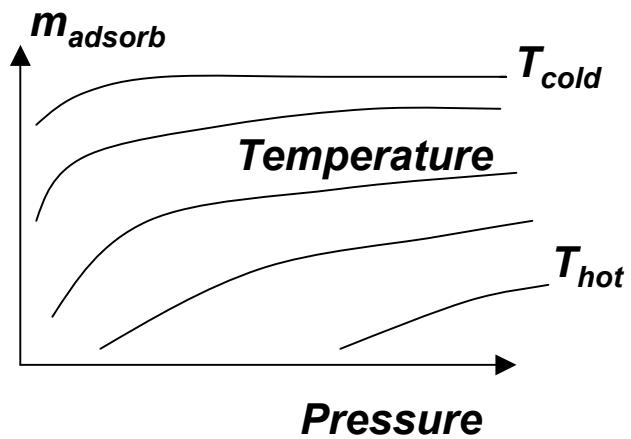
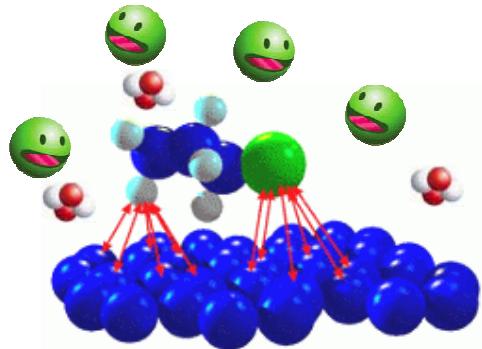
→ Cooling  
effect



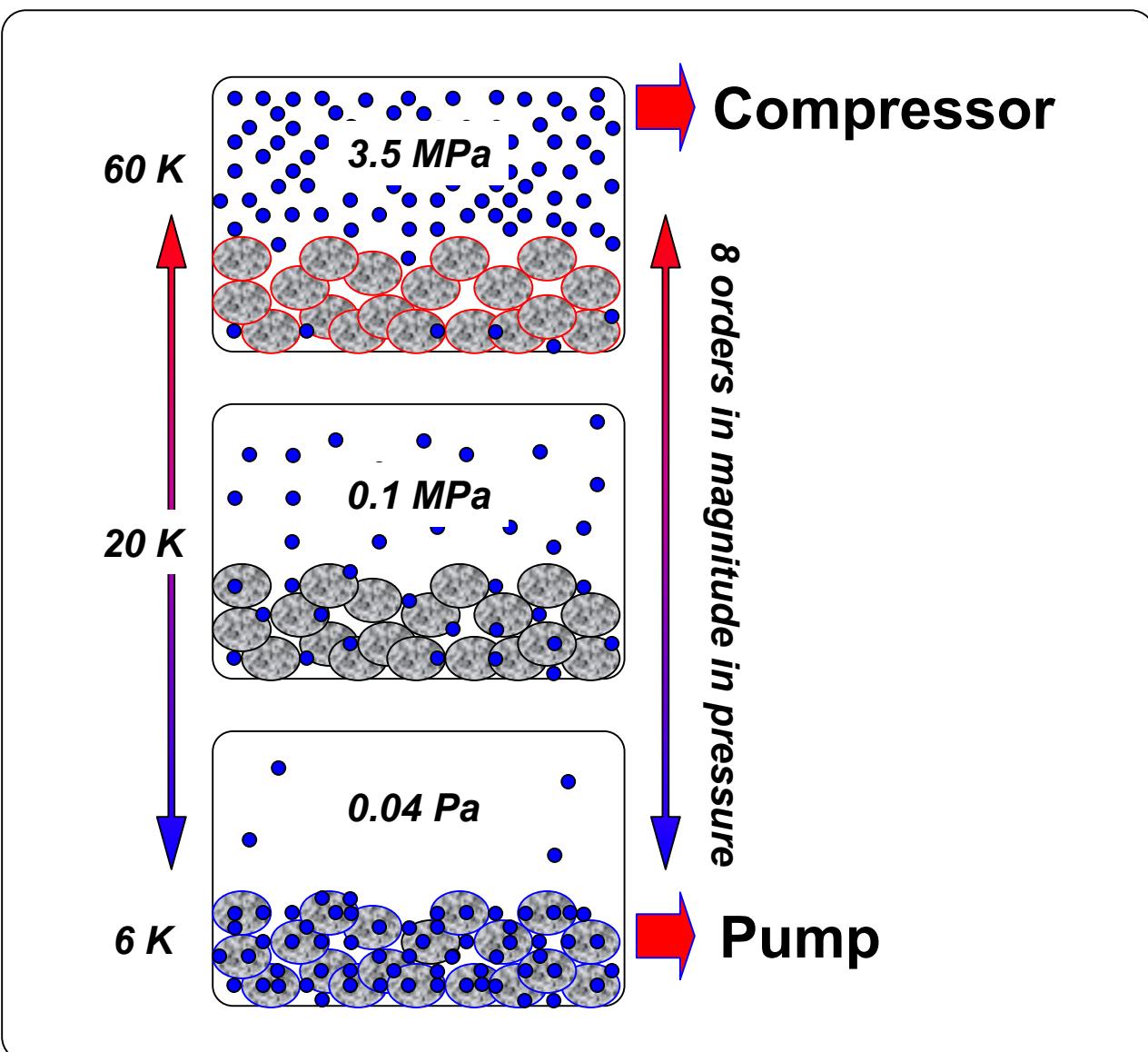
Over 6 Billions users !

# PHYSISORPTION

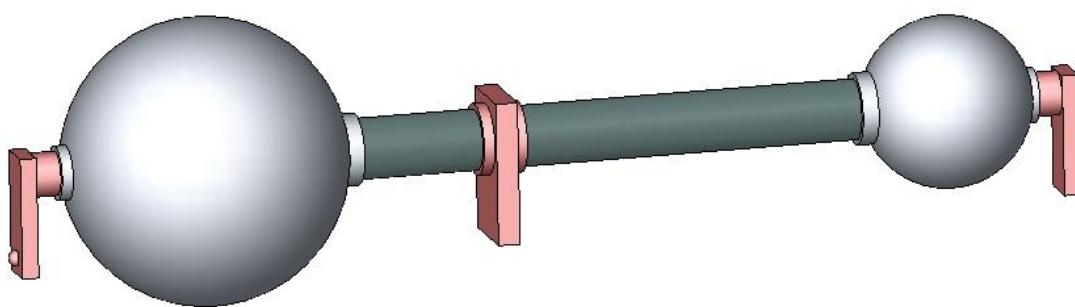
Make use of Van Der Walls forces



Need materials with large specific surface area ( $\text{cm}^2/\text{gr}$ )

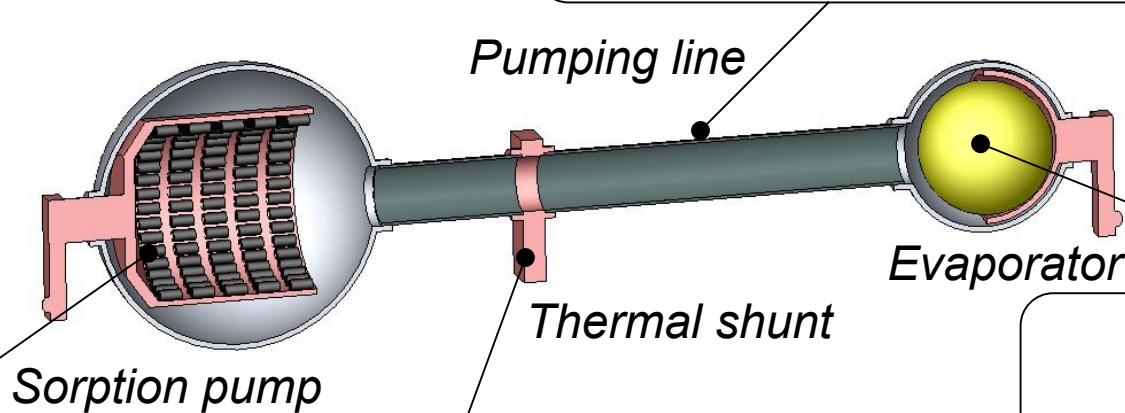


# SPACE BORNE SORPTION COOLER

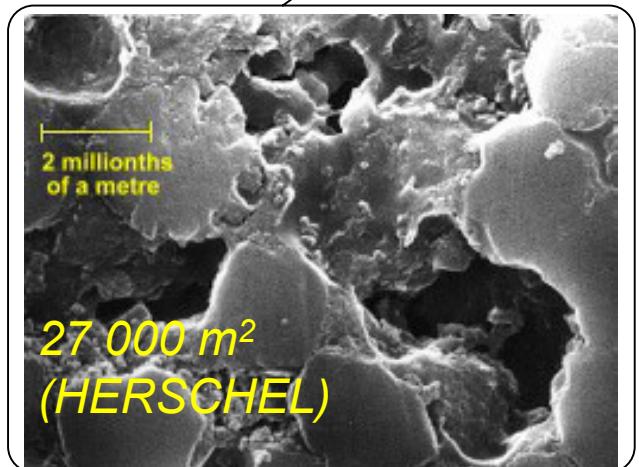


# SPACE BORNE SORPTION COOLER

*Geometry : thermal performance  
+ Leak Before Burst*

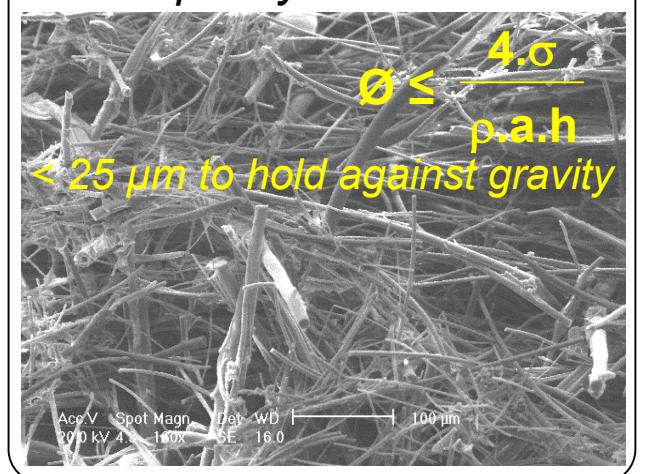


*Extraction of hot gaz enthalpy  
+ thermal conduction from line*

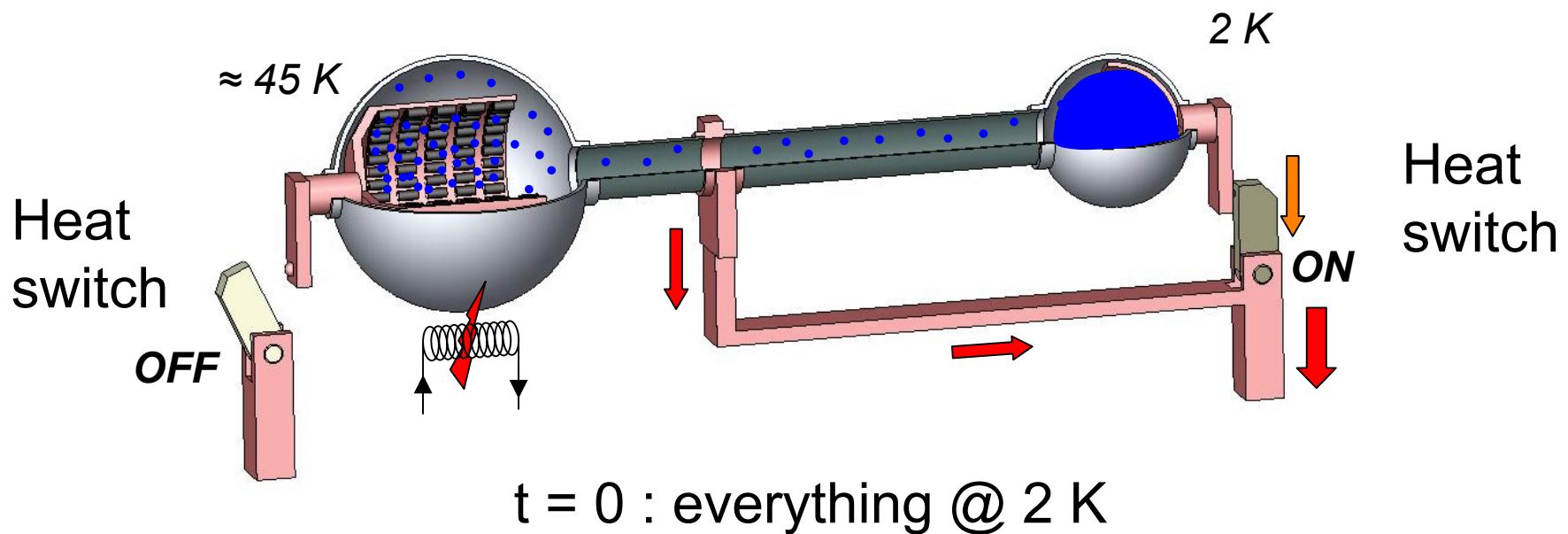


*Confinement by  
capillary attraction*

$$\Theta \leq \frac{4\sigma}{\rho \cdot a \cdot h}$$

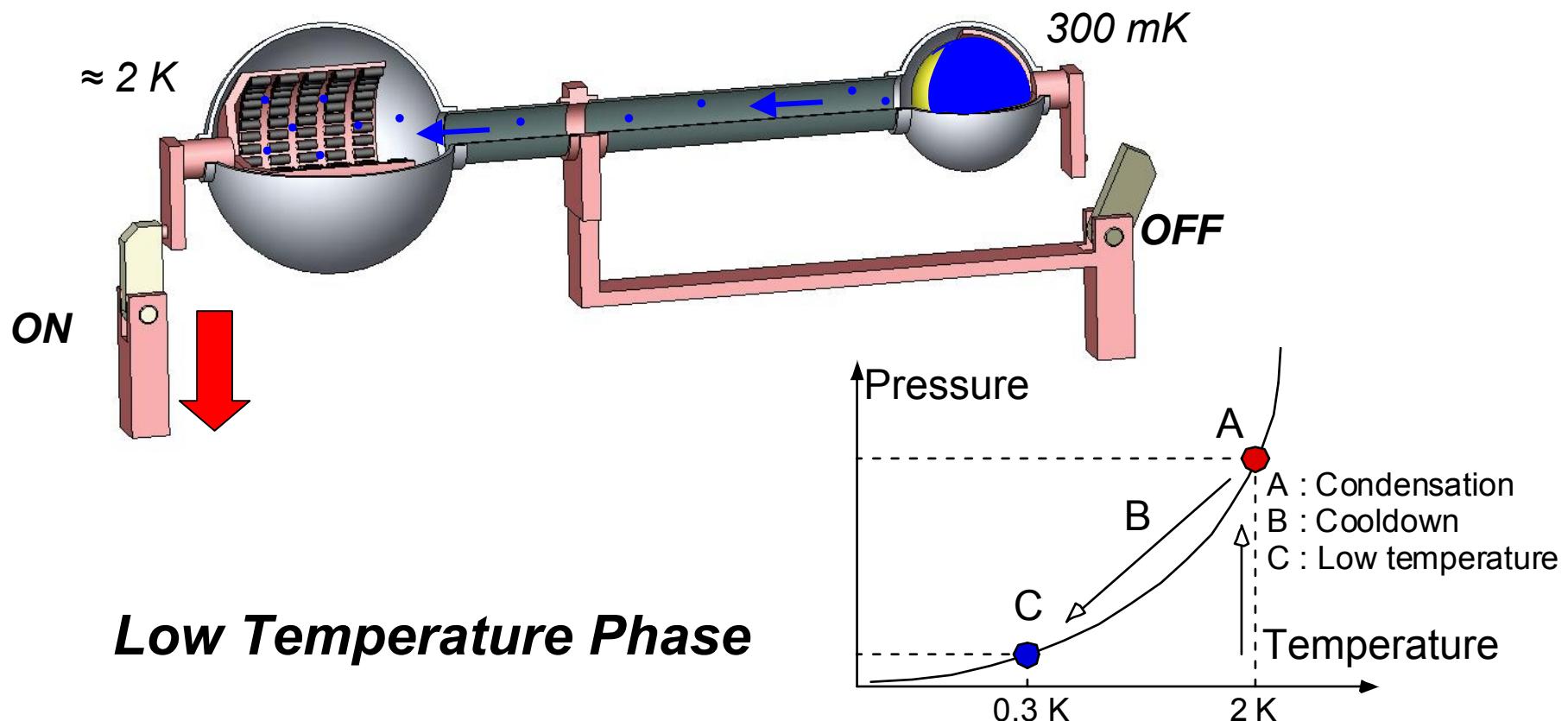


# SPACE BORNE SORPTION COOLER

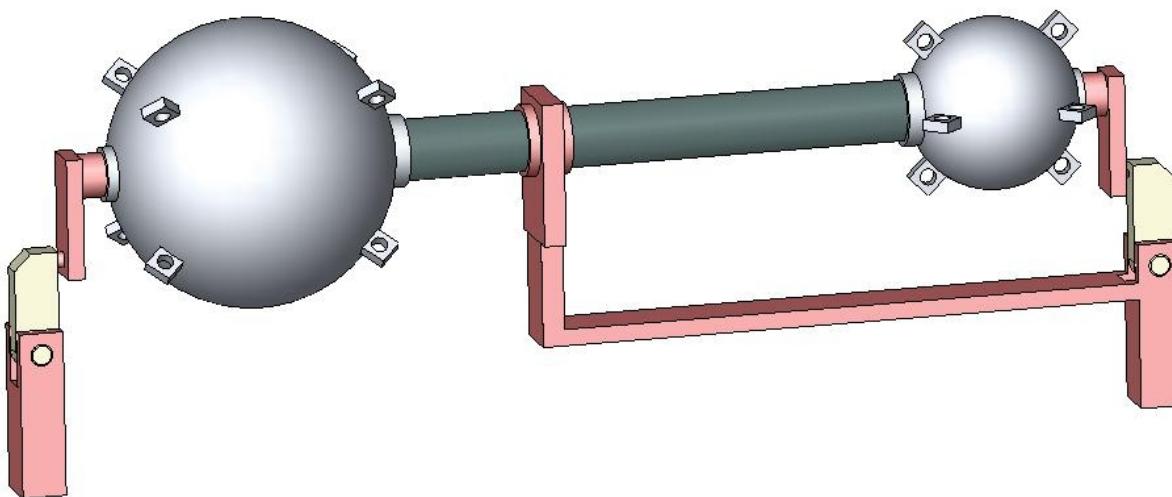


*Recycling Phase*

# SPACE BORNE SORPTION COOLER



# SPACE BORNE SORPTION COOLER

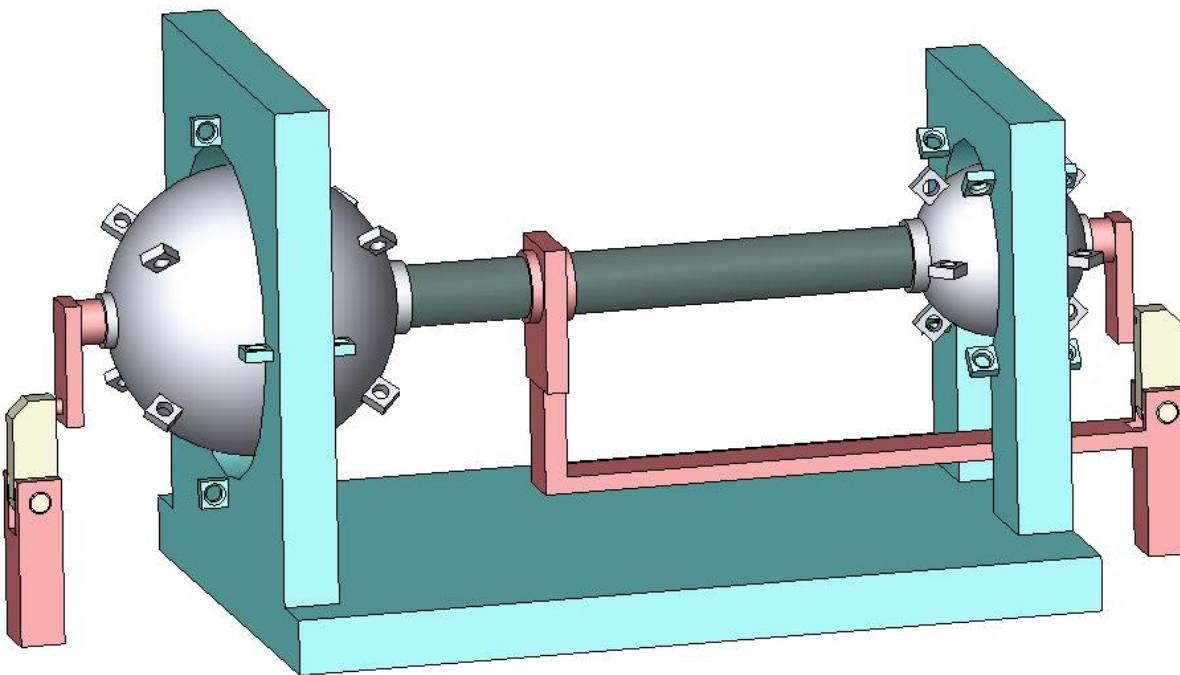


**Launch  
environment**



*firmly support but  
minimise conductive load*

# SPACE BORNE SORPTION COOLER

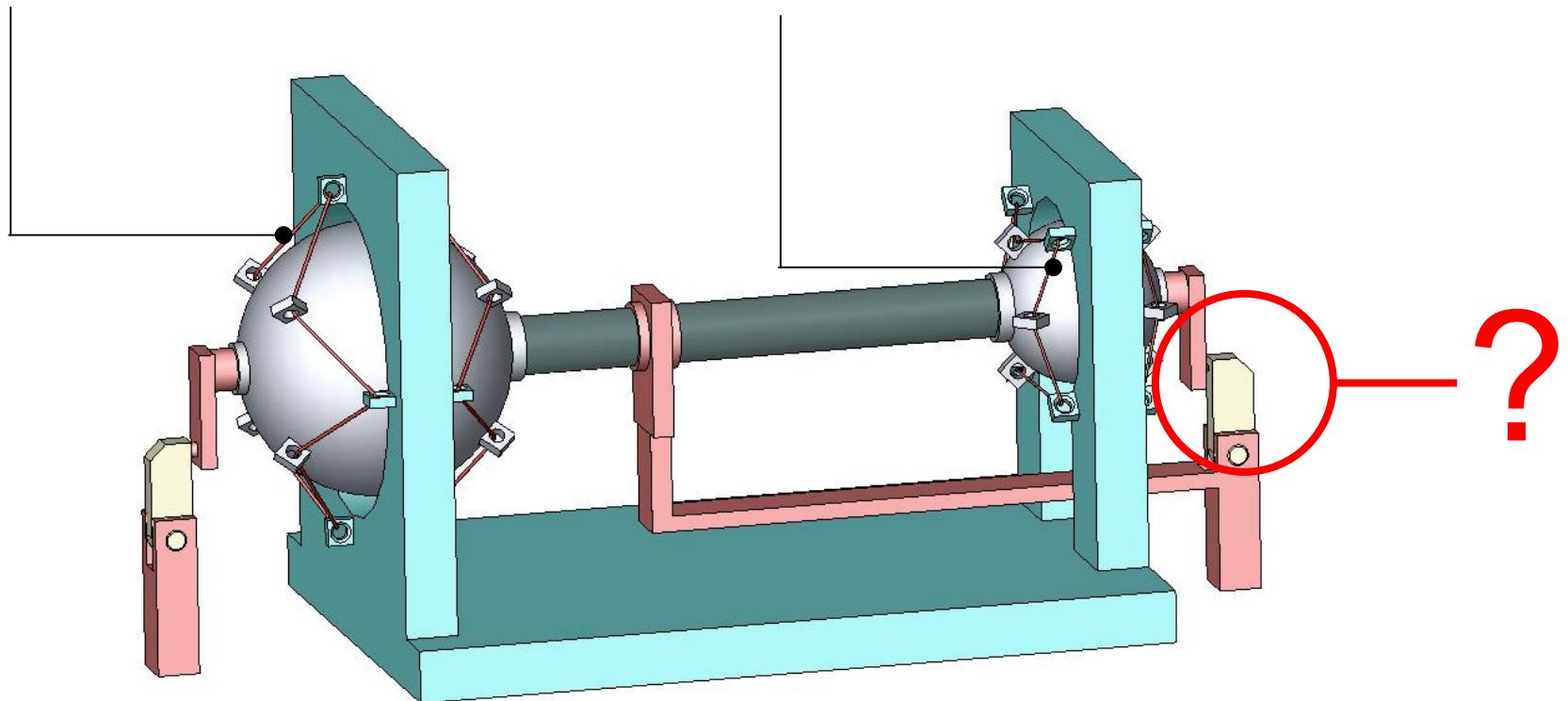


**Launch  
environment**



*firmly support but  
minimise conductive load*

## *Solution : Kevlar suspension system*

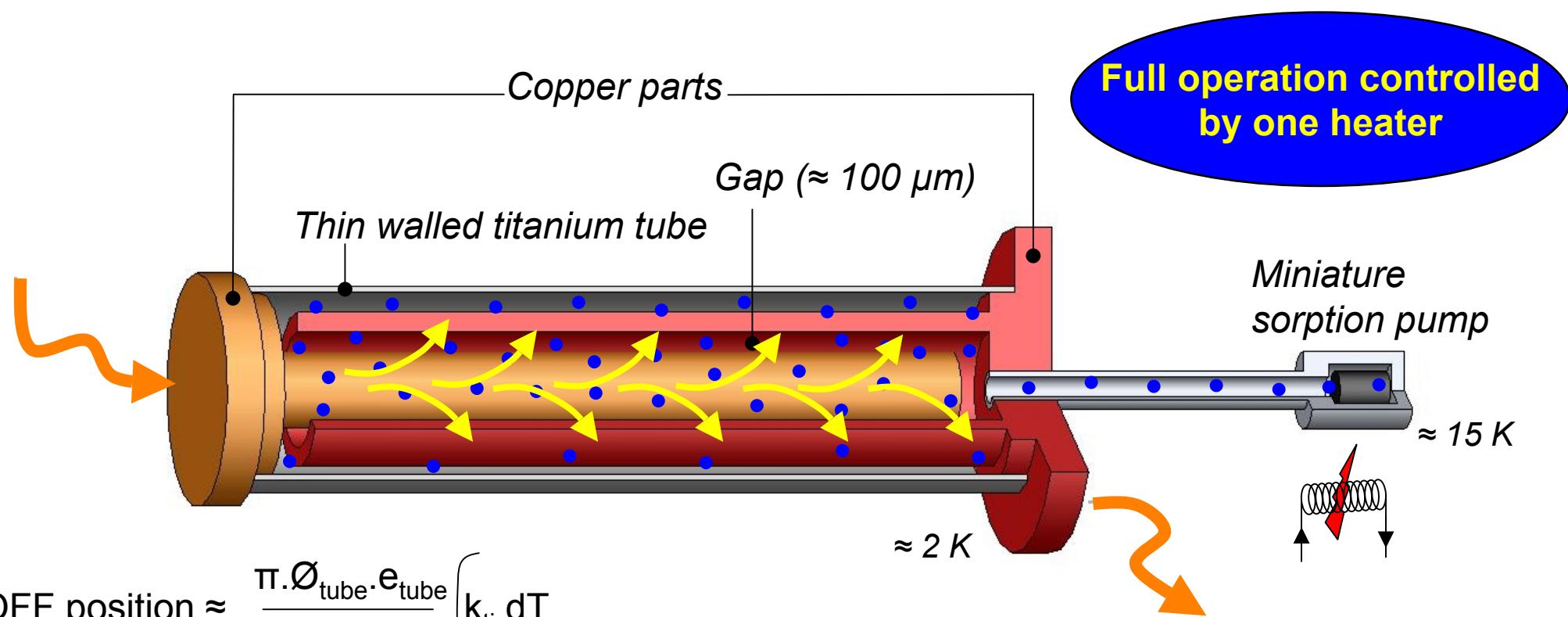


***Launch  
environment***



*firmly support but  
minimise conductive load*

# GAS GAP HEAT SWITCH



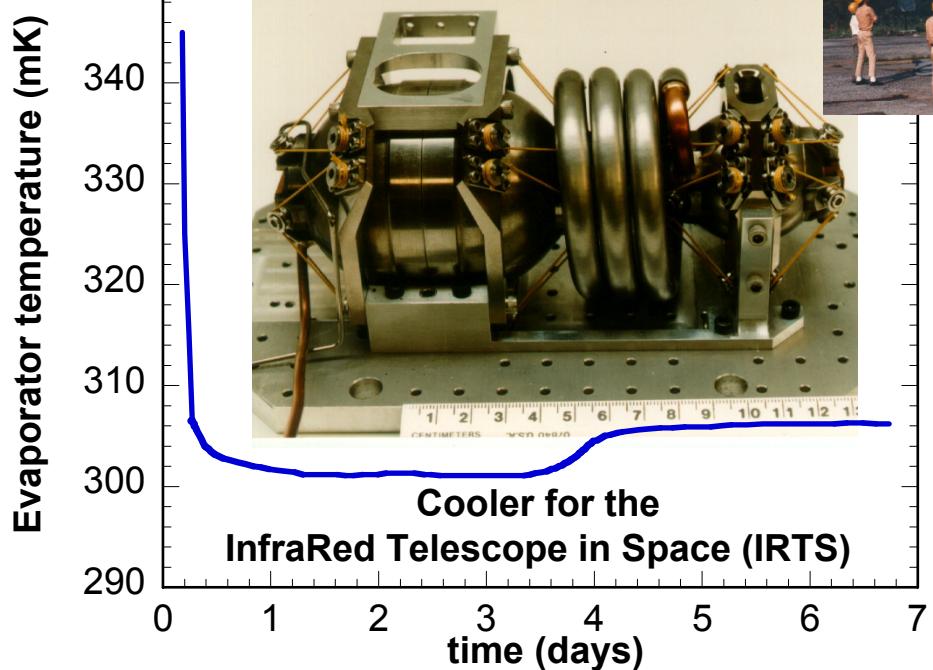
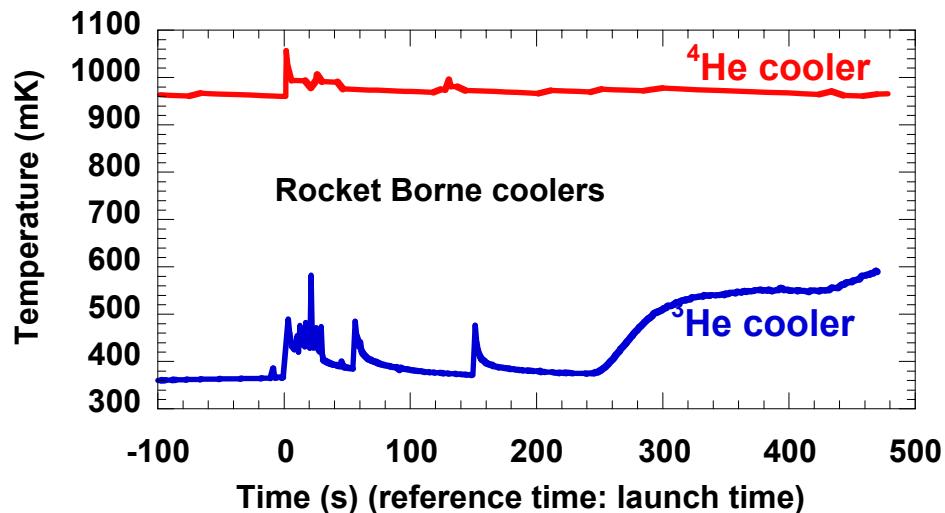
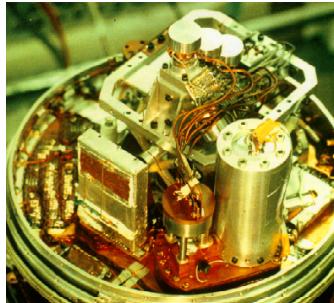
$$\text{OFF position} \approx \frac{\pi \cdot \varnothing_{\text{tube}} \cdot e_{\text{tube}}}{L_{\text{tube}}} \int k_{\text{ti}} dT$$

$$\text{ON position} \approx \frac{\pi \cdot \varnothing_{\text{cu}} \cdot L_{\text{cu}}}{\text{Gap}} \int k_{\text{gaz}} dT$$

**Ratio  $\geq 6000$**

- Simple
- Reliable
- Compact
- Vibration free
- Lightweight
- Electromagnetically clean
- No moving part
- $\approx$  Gravity independent

## Rocket Borne & Orbital coolers

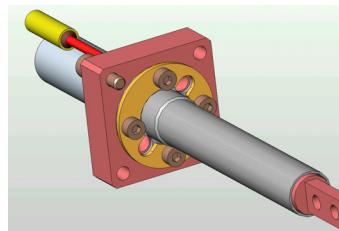
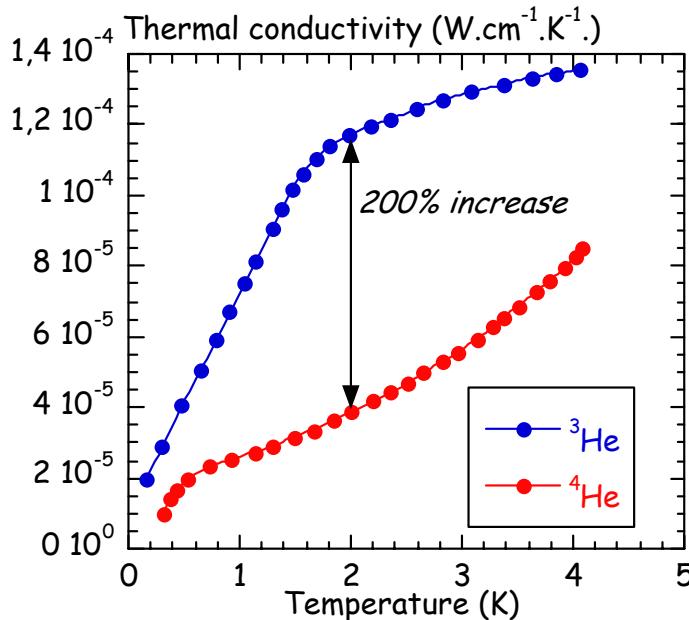


Successfully flown onboard Japanese Space Flyer Unit On March 1995

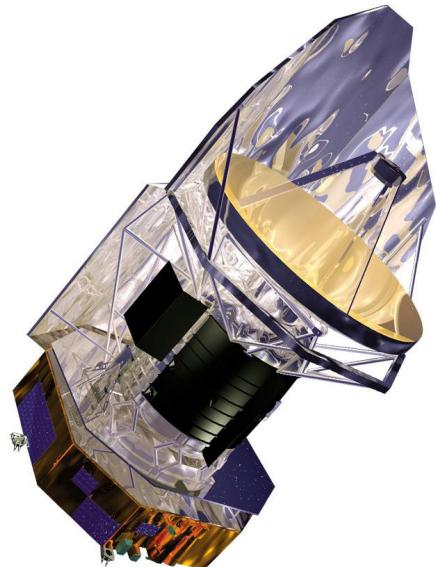
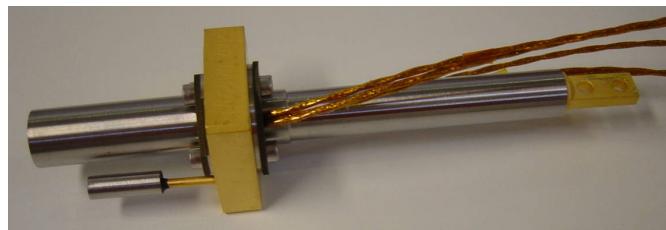


EM cooler - ESA TRP Contract  
Qualification program successfully performed

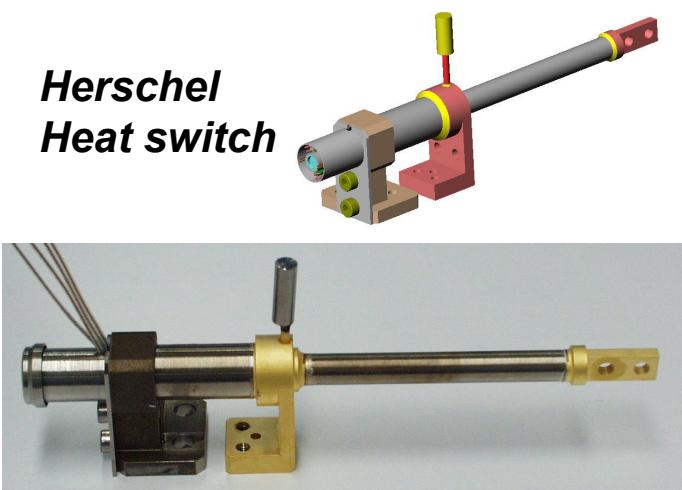
# GG HEAT SWITCH : HERSCHEL/PLANCK SATELLITE



**Planck Heat switch**



**Herschel Heat switch**



**MAIN CHARACTERISTICS**  
**Mostly made of Titanium Ta6V + copper**

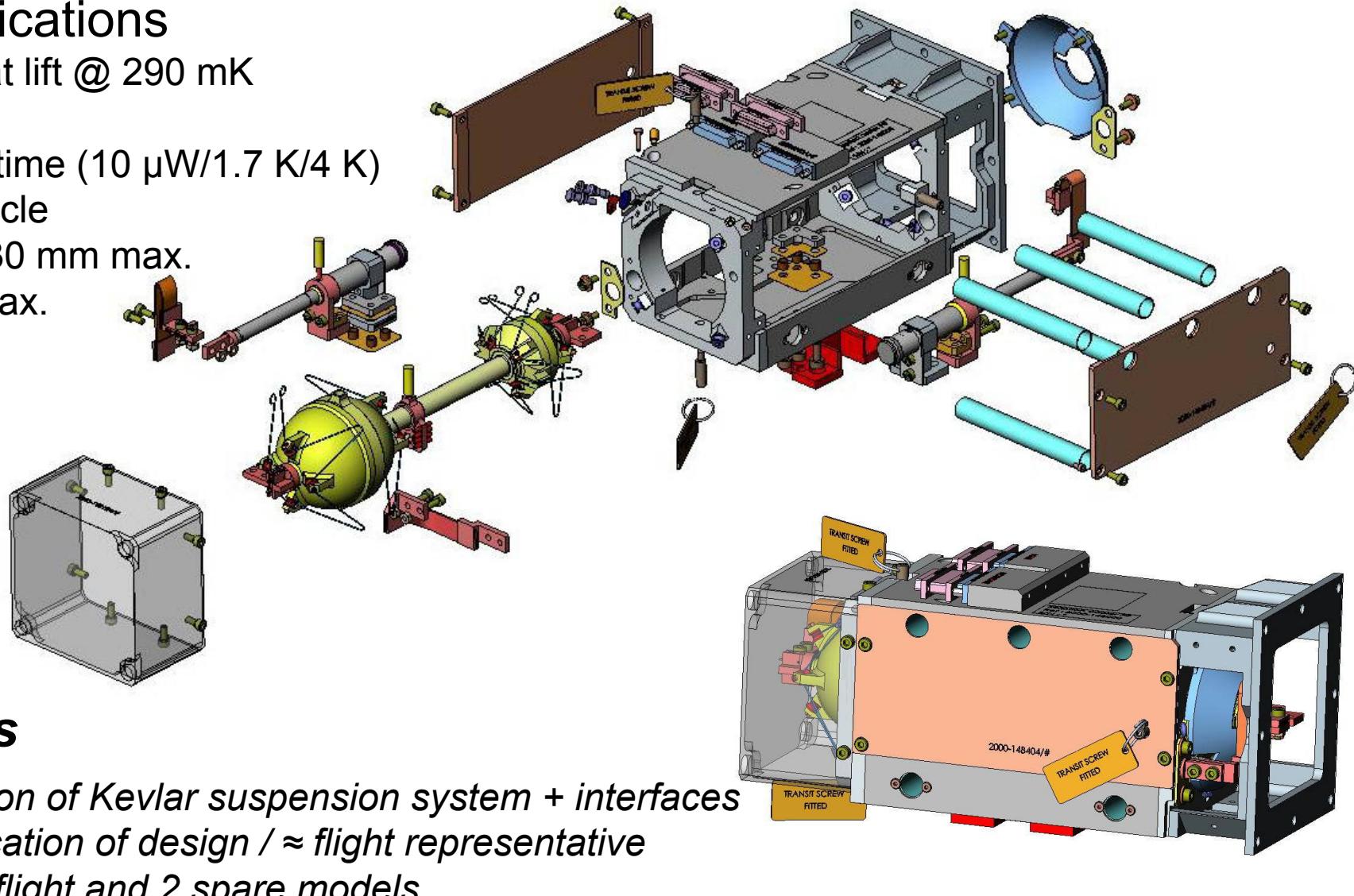
- mass  $\approx$  70 grams
- overall length : 140 mm

**Typical performance @ 1.8 K :**

- OFF position : 6  $\mu\text{W/K}$
- ON position : 50 mW/K
- ON/OFF ratio  $>$  7000
- Switching temperature :  $\approx$  14 K
- Input power (ON) :  $<$  400  $\mu\text{W}$

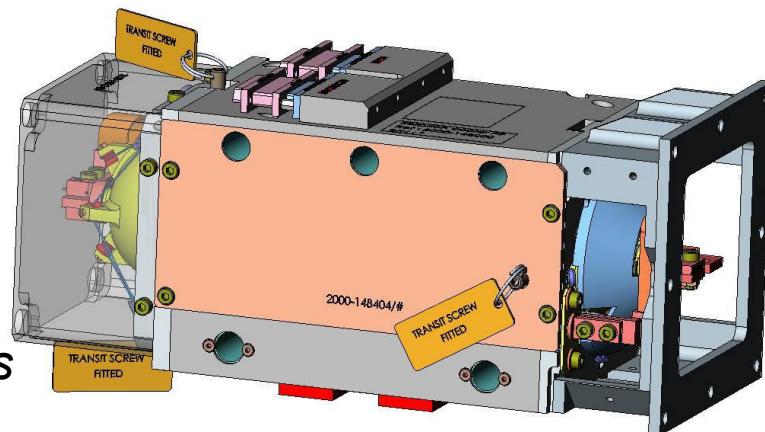
## Main specifications

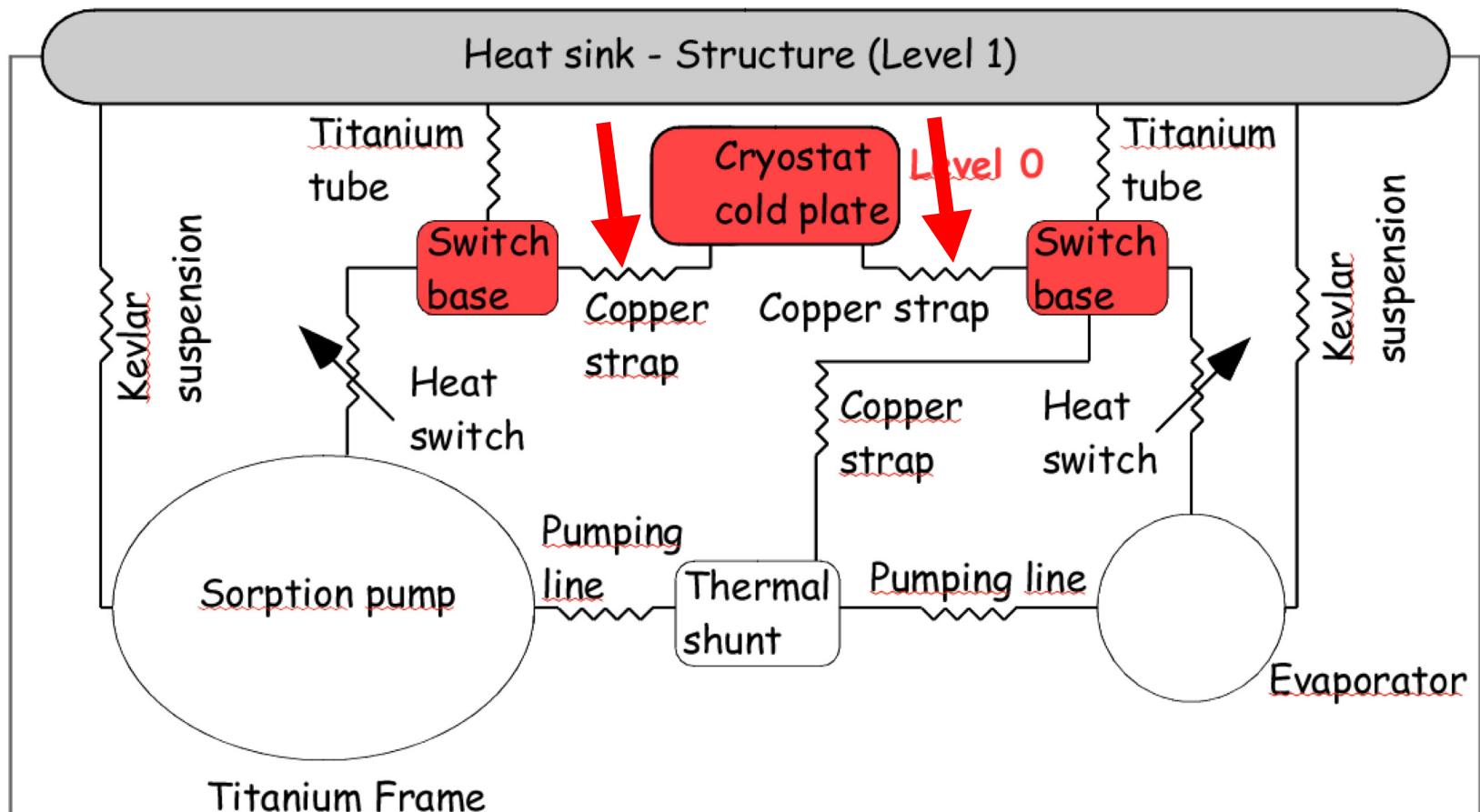
- 10  $\mu\text{W}$  net heat lift @ 290 mK
- 2 h recycling
- 46 h min hold time (10  $\mu\text{W}/1.7 \text{ K}/4 \text{ K}$ )
- 860 J max. /cycle
- 100 x 100 x 230 mm max.
- 1800 grams max.



## 8 models

- 2 STM : validation of Kevlar suspension system + interfaces  
2 CQM : qualification of design /  $\approx$  flight representative  
2 FM / 2 FS : 2 flight and 2 spare models





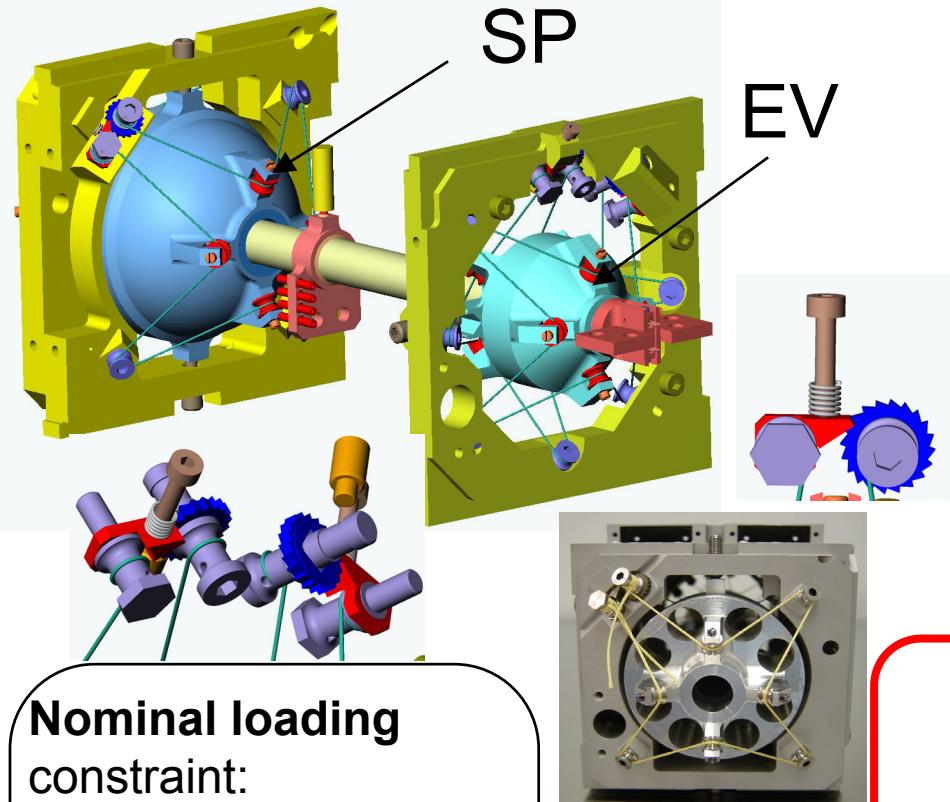
1.7 & 4 K heat sinks



Design and performance driver !

*2 thermal bus to level 0 needed !*

# KEVLAR SUSPENSION SYSTEM



## Nominal loading

constraint:

EV\* : 5 DaN / 757 MPa

SP : 15 DaN / 760 MPa

(breaking strength 1600 MPa)

\*:SPIRE case  
(PACS : 15 DaN)

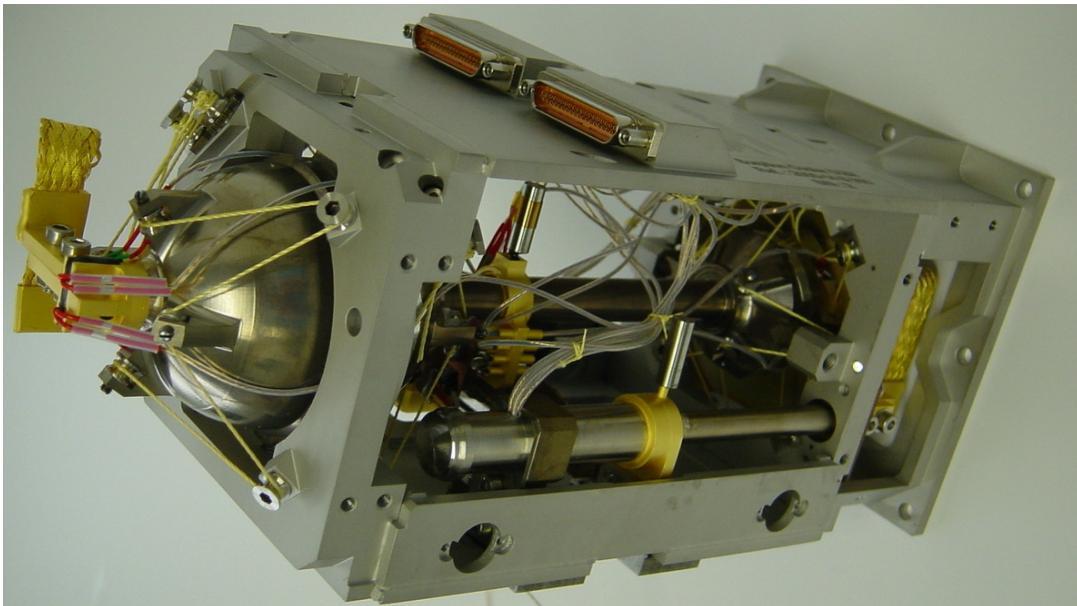
	Nylon	S. Steel	Ta6V	Kevlar 29
s (MPa)	100	550	875	1600
Y (MPa)	3000	200 000	110 000	65 000
$I = \int_{0.3}^2 k dT$	$5.9 \cdot 10^{-5}$	$2 \cdot 10^{-3}$	$10^{-3}$	$7 \cdot 10^{-5}$
$sY^{0.5}/I$	$0.9 \cdot 10^8$	$1.2 \cdot 10^8$	$2.9 \cdot 10^8$	$58 \cdot 10^8$

Keeping resonant frequencies the same  
 Titanium → load X 8.6 !  
 Nylon → load X 25.7

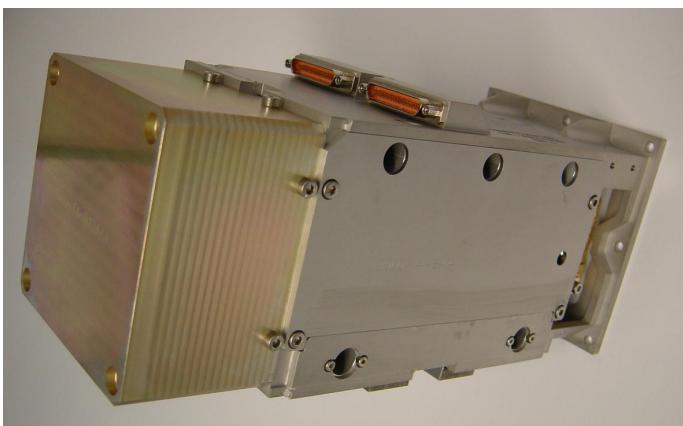


- Creep under tension and thermal cycling
- Young's modulus hysteresis (tension dependent)
- Negative thermal expansion
- Abrasion sensitive
- Weakness in transverse direction

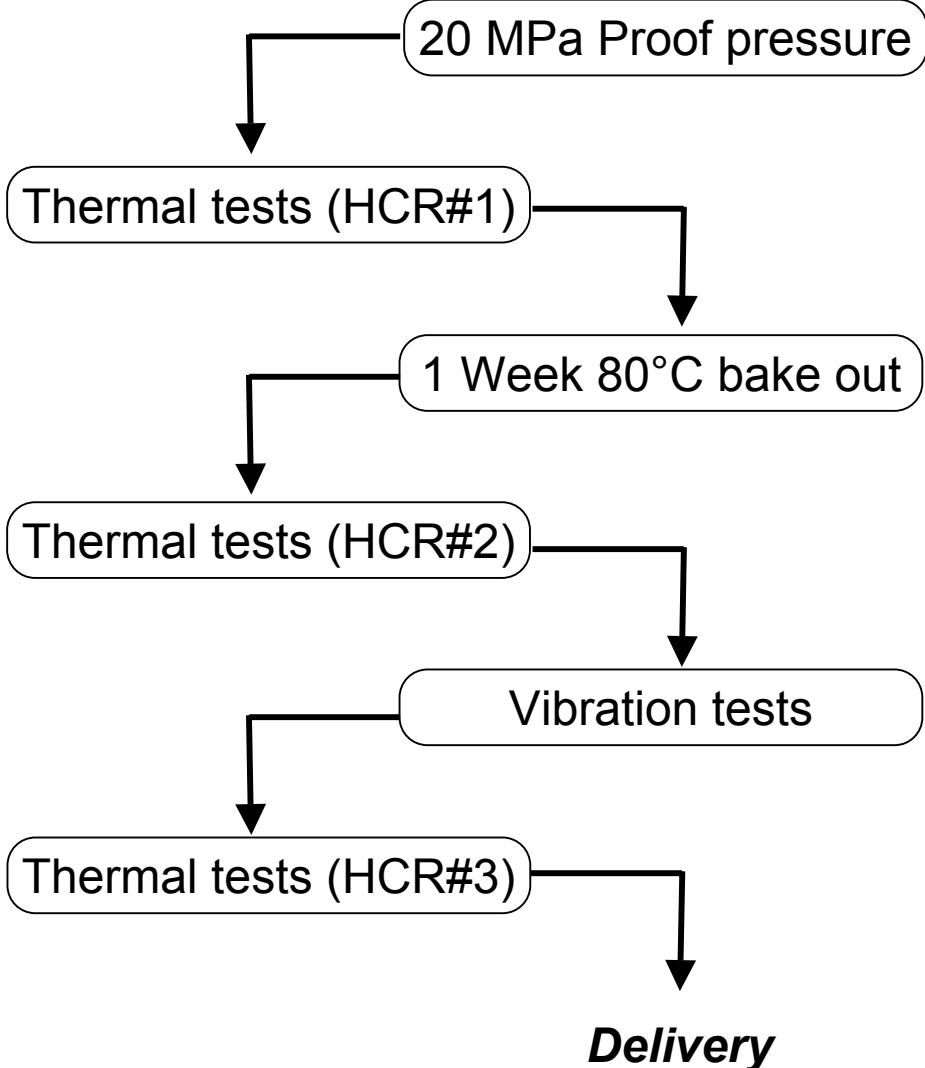
# CQM : QUALIFICATION PROGRAM



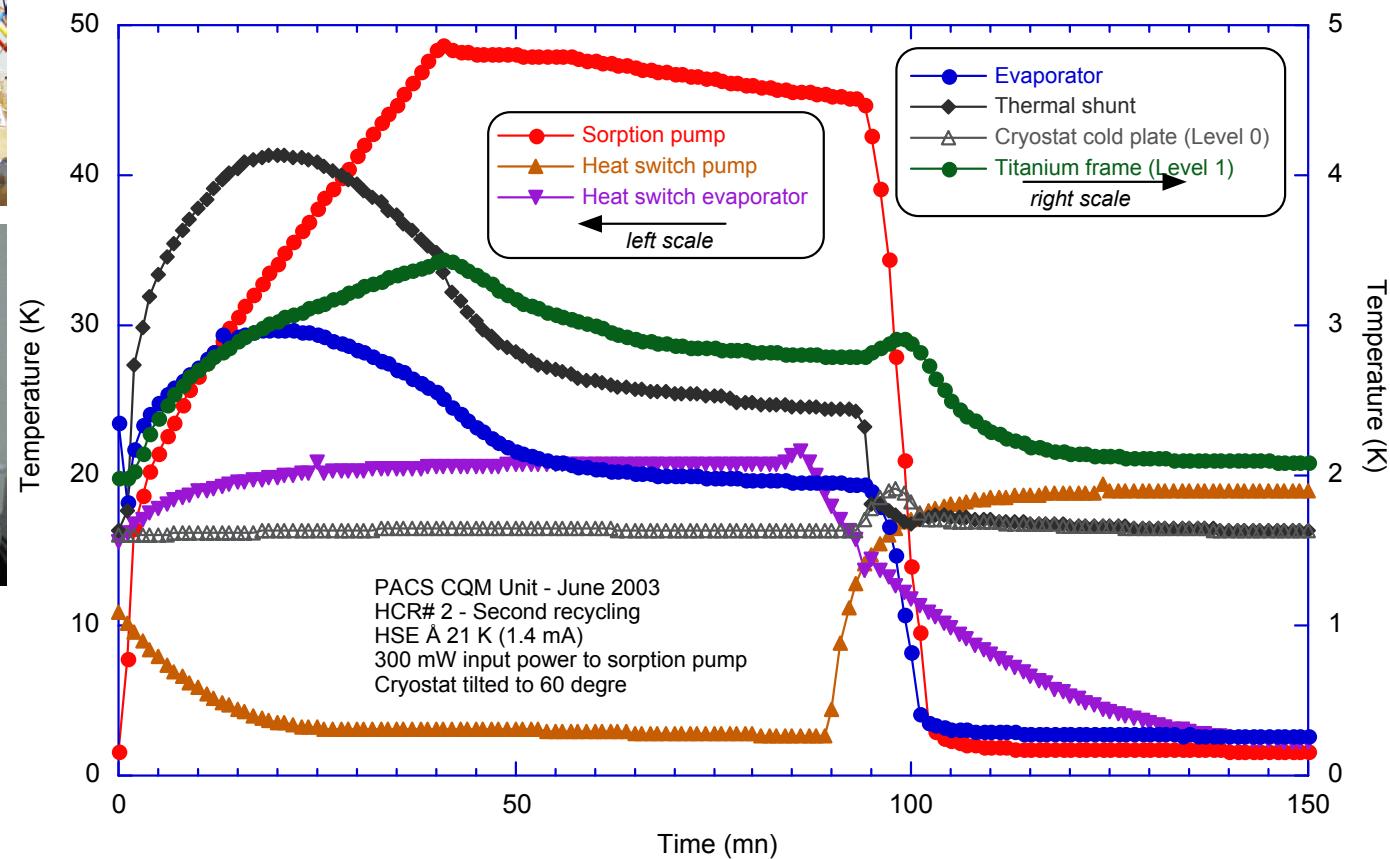
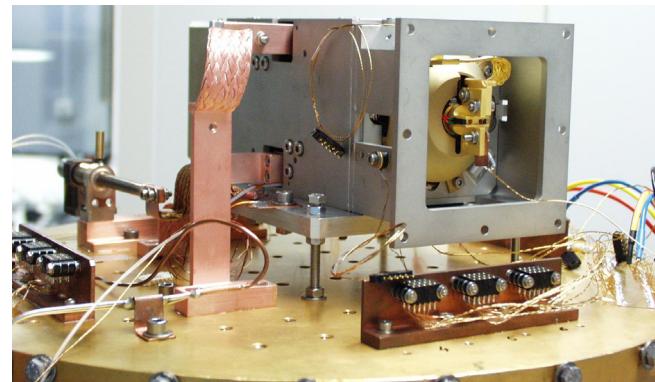
**SPIRE : 290 $\mu$ m/500  $\mu$ m strings**  
**PACS : all strings 500  $\mu$ m**



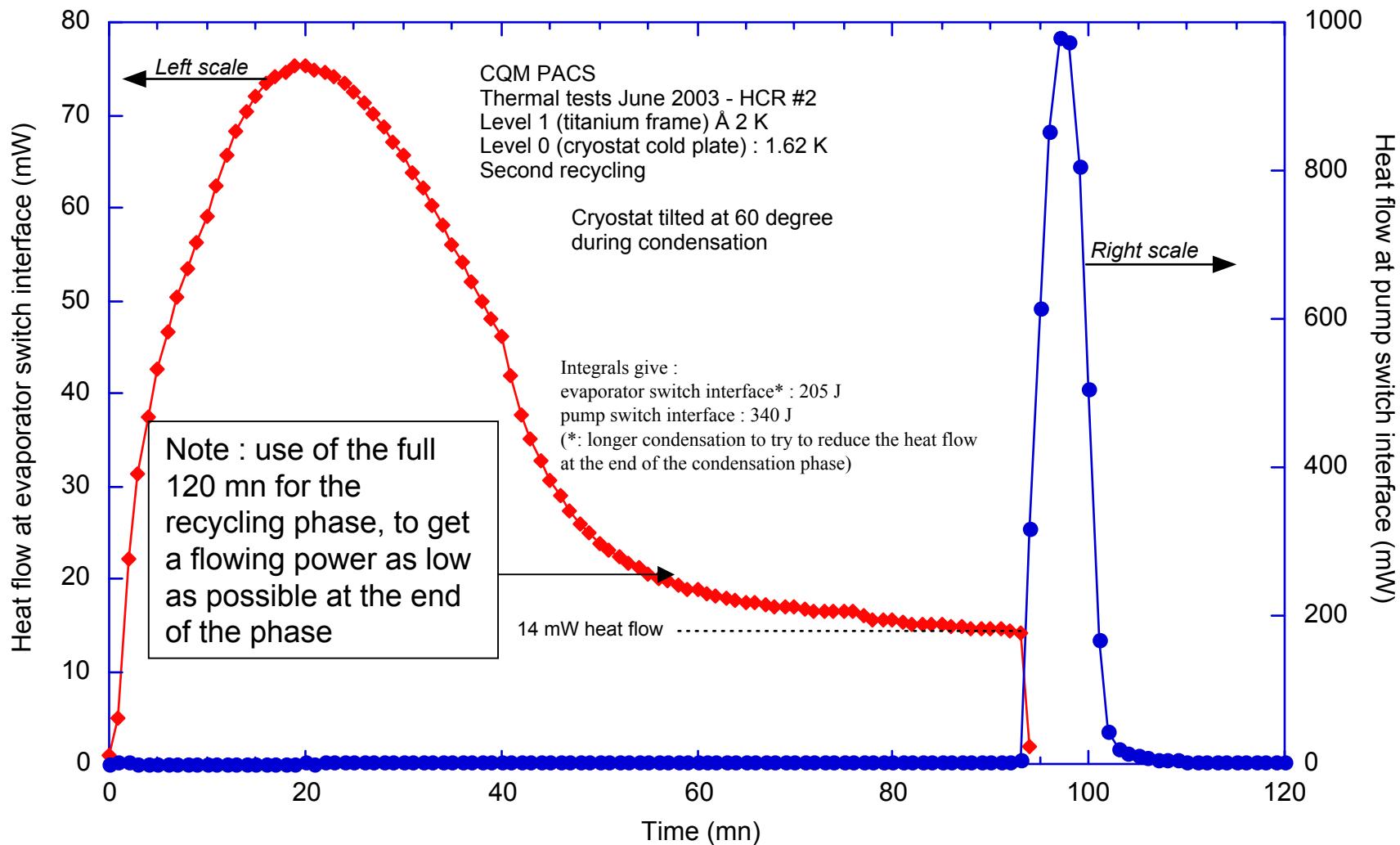
## QUALIFICATION PROGRAM



# CQM : RECYCLING PHASE



# CQM : HEAT FLOWS



# CQM : VIBRATION TESTS

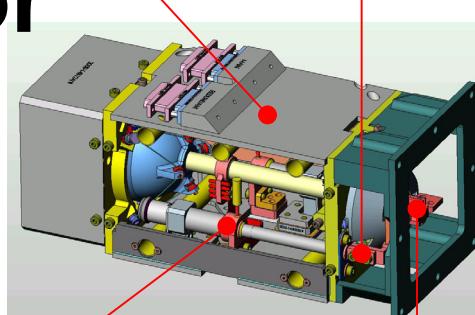
Room  
Temperature  
Tests



		X	Y	Z
SPIRE	Sinus	[25-60] 22.5 G	[25-60] 15 G	[25-60] 15 G
	Random [20-2000]	5 Grms	6 Grms	6 Grms
PACS	Sinus	[5-100] 18 G	[5-100] 8 G	[5-100] 8 G
	Random [2-2000]	11.5 Grms	4.9 Grms	2.54 Grms

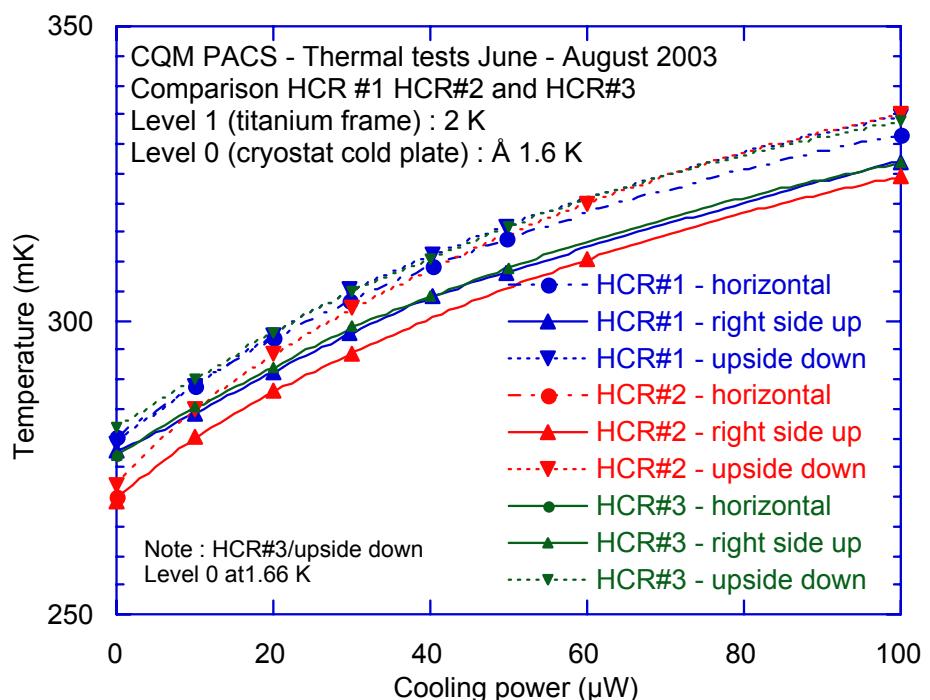
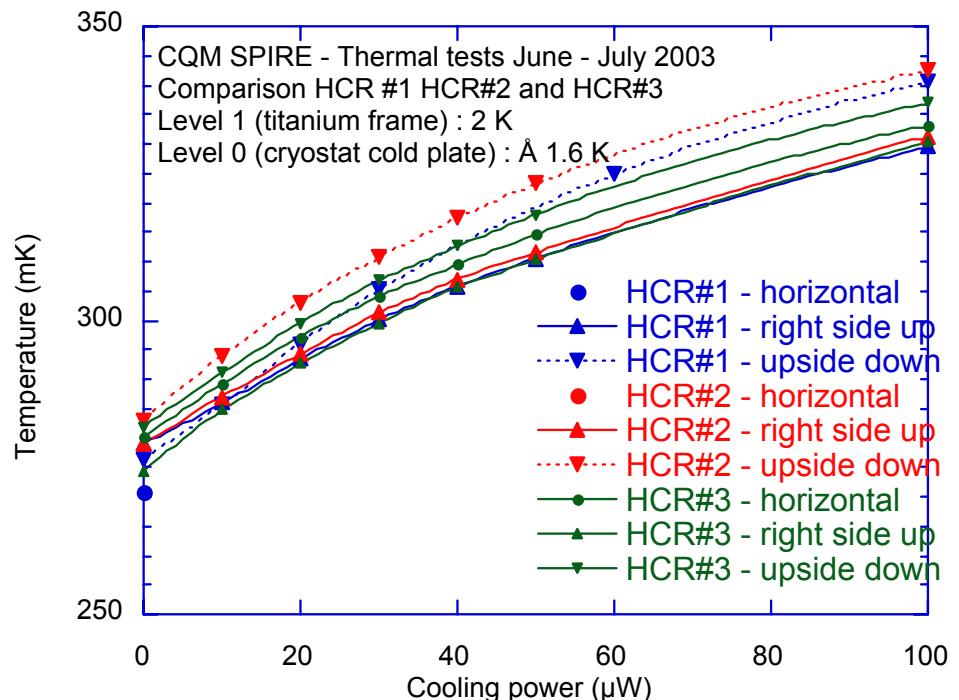
	Cold tip	Structure	HS evap. I/F	HS pump I/F
X <sub>SPIRE</sub>	386 / 15	826 / 3.7	138 / 1.9 339 / 19.5	138 / 1.7 368 / 9
Y <sub>SPIRE</sub>	561 / 23.3	1360 / 1.36	705 / 14.8	705 / 17
Z <sub>SPIRE</sub>	291 / 2.6 397 / 11.7	1130 / 1.8 1580 / 5.8	127 / 1.7 293 / 17.2	136 / 2.8 295 / 12.1
X <sub>PACS</sub>	558 / 21	1230 / 3.9 1580 / 5.5	126 / 1.6 337 / 17	132 / 1.8 360 / 14.6
Y <sub>PACS</sub>	653 / 21	1180 / 3.5 1380 / 3.8	302 / 2.8 653 / 14.5	325 / 4.3 761 / 13
Z <sub>PACS</sub>	460 / 2.7 532 / 25.6	923 / 6.3 1010 / 5.6	128 / 2.1 305 / 7	134 / 2.6 320 / 7

No major  
failure  
(lost 1 wire)



XX / YY :  
XX : resonant frequency  
YY : corresponding G  
(0.5 G excitation)

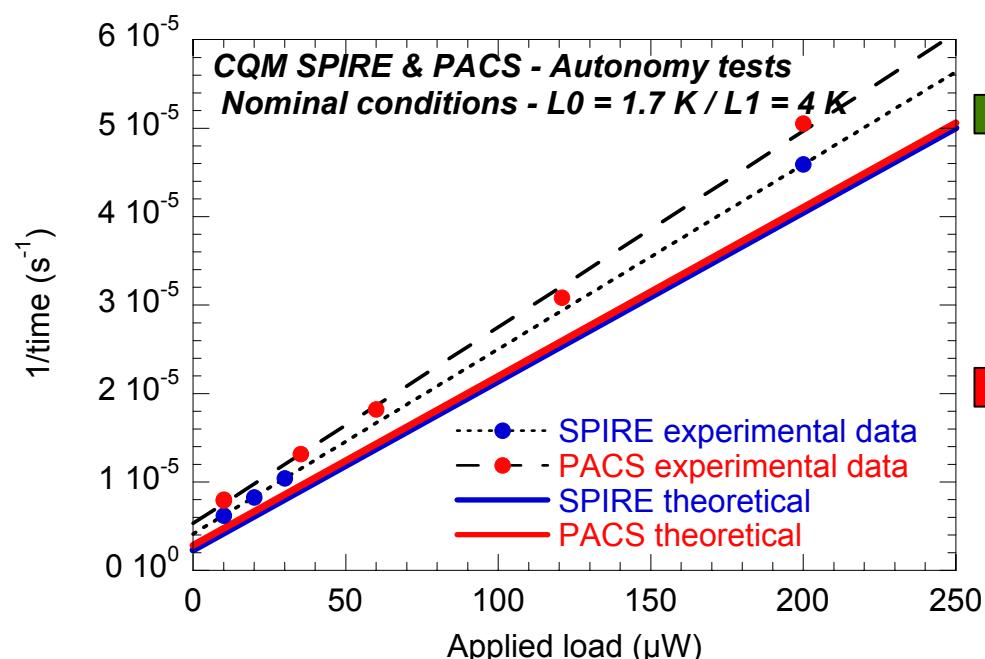
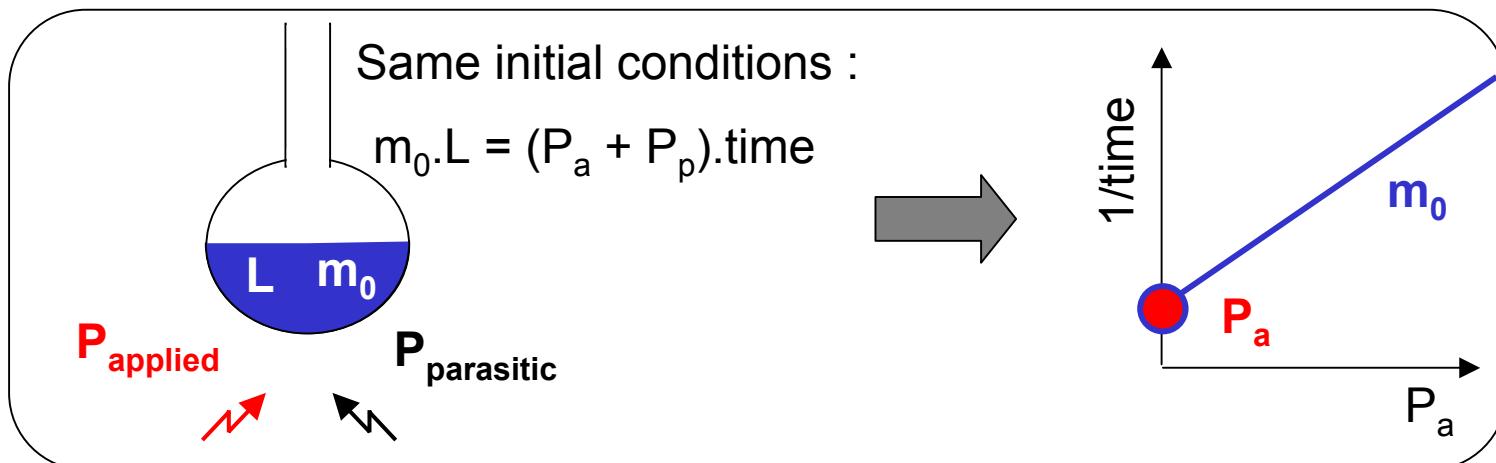
# CQM : COOLING POWERS



No significant difference between HCR#1, HCR#2 and HCR#3  
 or rather results consistent within  $\pm 5$  mK

(HCR : Health Check Report)

# CQM : AUTONOMY TESTS



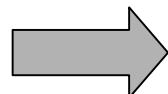
**Coolers undercharged by  $\approx 10\%$**

Cannot be corrected for CQM  
 Considered as minor  
 New filling procedure

**Extra parasitic of 8 to 10  $\mu\text{W}$**

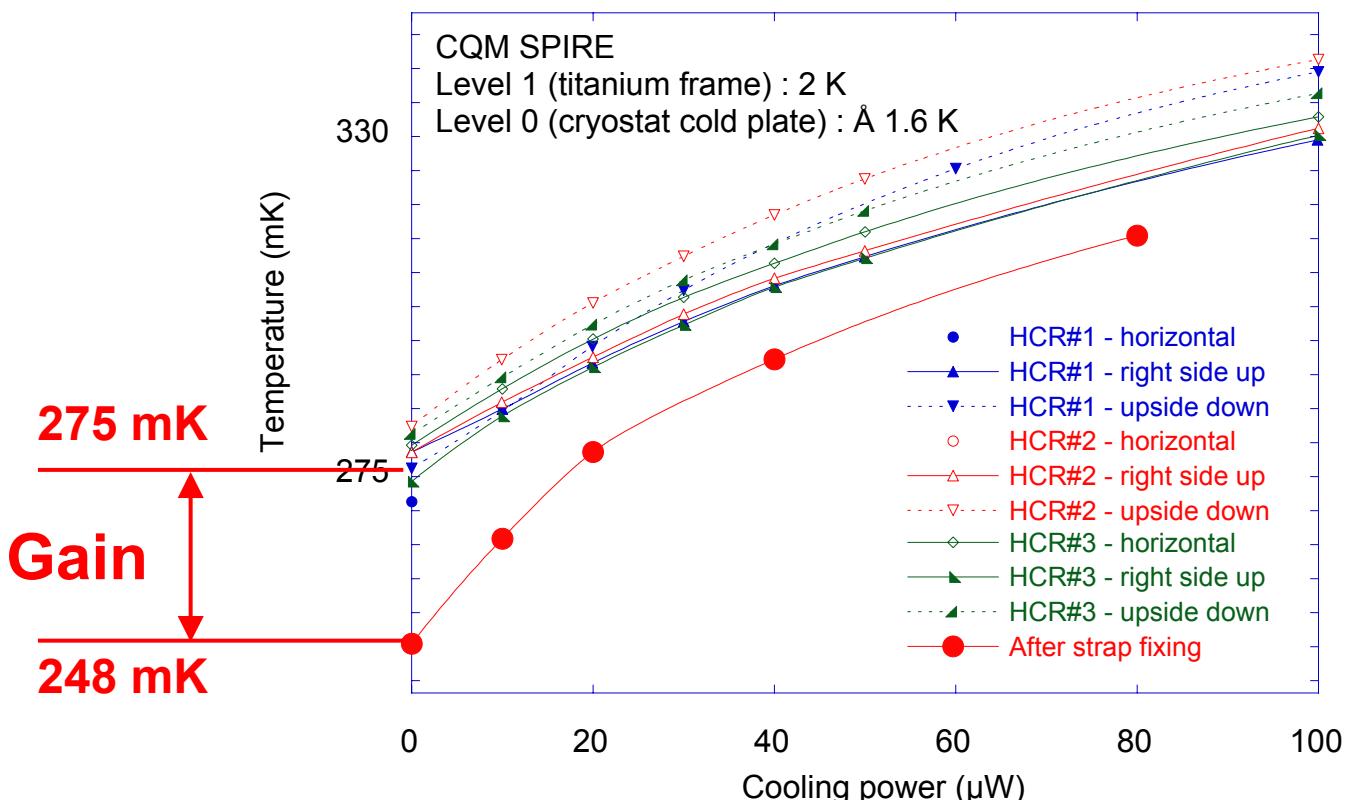
**Problem identified :**  
 heat switch + gold plated strap  
 Strap : mechanical constraint on heat switch

*Cooler operated without strap between switch and evaporator :*



**Redesign of thermal strap :**

**SPIRE CQM**



**PACS CQM**

*Nominal conditions :  
 $L_0 = 1.7 \text{ K}$  -  $L_1 = 4 \text{ K}$*

**With 10  $\mu\text{W}$  applied load**

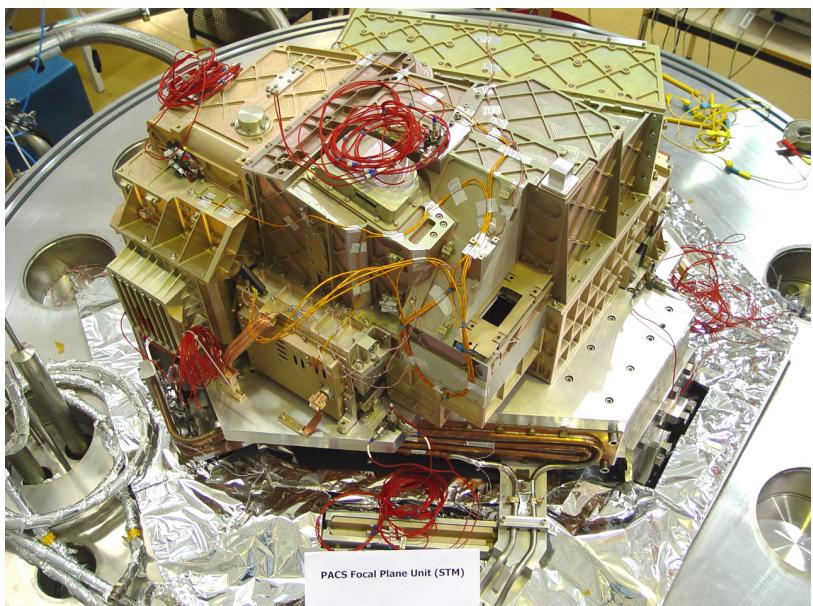
**47 hours @ 291 mK**

**Analysis of data**

**Parasitic of 13  $\mu\text{W}$   
(predicted 14  $\mu\text{W}$ )**

# HERSCHEL COOLERS : STATUS

- 2 structural and 2 qualification models successfully developed and qualified



- FM manufacturing in progress

*L. Clerc, D. Communal, M. Dubois (BV), JL. Durand, E. Ercolani,  
L. Guillemet, N. Luchier, L. Miquet, R. Vallcorba, L. Duband*



# SORPTION COOLER : TEMPERATURE REGULATION

## Power to evaporator

- "efficient" but

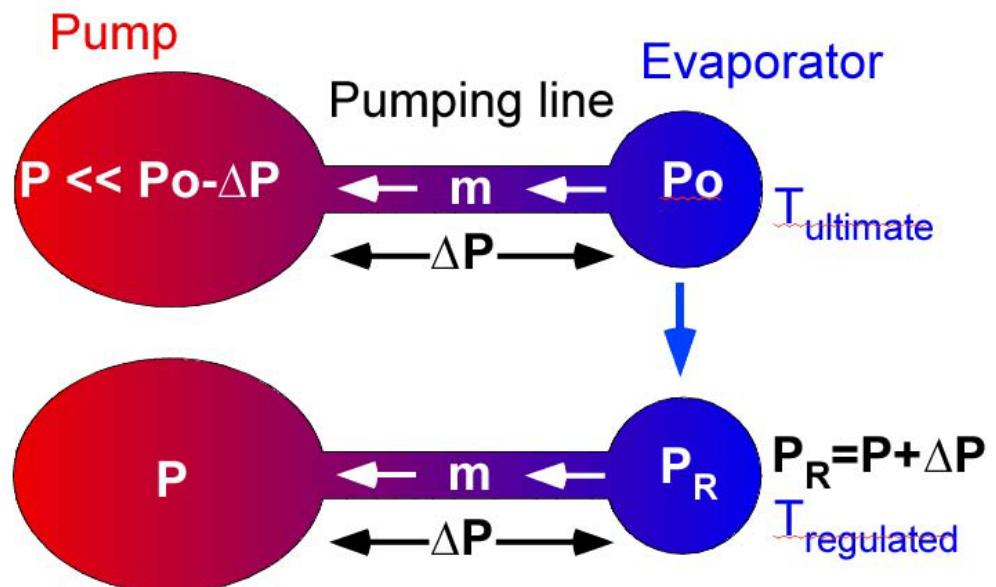
added heat load



*Reduced hold time*

*- Critical if T high -*

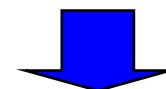
## Regulate T sorption pump



*Does not affect hold time*

(increases it)

*Full range  $T_{\text{ultimate}}$  to  $T_{\text{cold plate}}$*



# SORPTION COOLER : ULTIMATE TEMPERATURE ?

Neglecting switch, support, detector, etc..., as a first approximation :

## Mass flow rate

$$\dot{m} = \frac{f_1(T) \cdot \phi^2}{L} \cdot HP$$

## Pressure above the bath

viscous

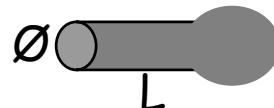
$$P_{\text{bath}} = \frac{f_2(T) \cdot \sqrt{m \cdot L}}{\phi^2}$$

molecular

$$P_{\text{bath}} = \frac{f_3(T) \cdot m \cdot L}{\phi^3}$$

## Single Stage

$$f_1, f_2, f_3(T) \approx \text{Cte}$$



[Note : when load from switch, support, detector, etc.. taken into account : significant impact on above numbers]

$$P_{\text{bath}} \% \frac{1}{\phi}$$

But !

$$\text{Hold time \%} \frac{L \cdot M_{\text{He3}}}{\phi^2}$$

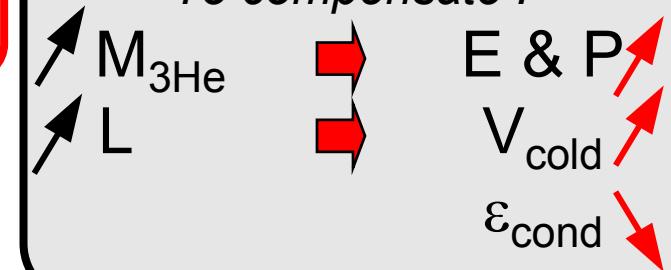
Example : 10% gain

$$\begin{array}{l} 280 \text{ mK} \\ 0.9 \cdot 10^{-3} \end{array} \xrightarrow{\quad} \begin{array}{l} 250 \text{ mK} \\ 0.24 \cdot 10^{-3} \end{array}$$

$$\phi \times 3.7$$

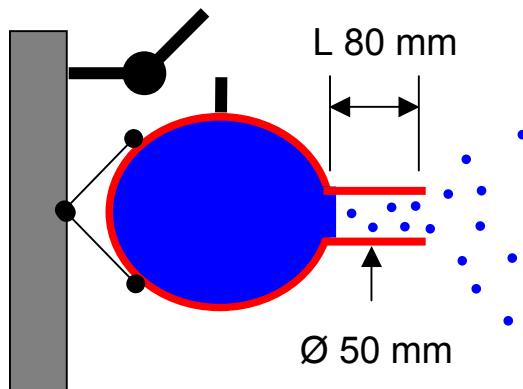
Hold time  $\div$  by 14 !

To compensate :

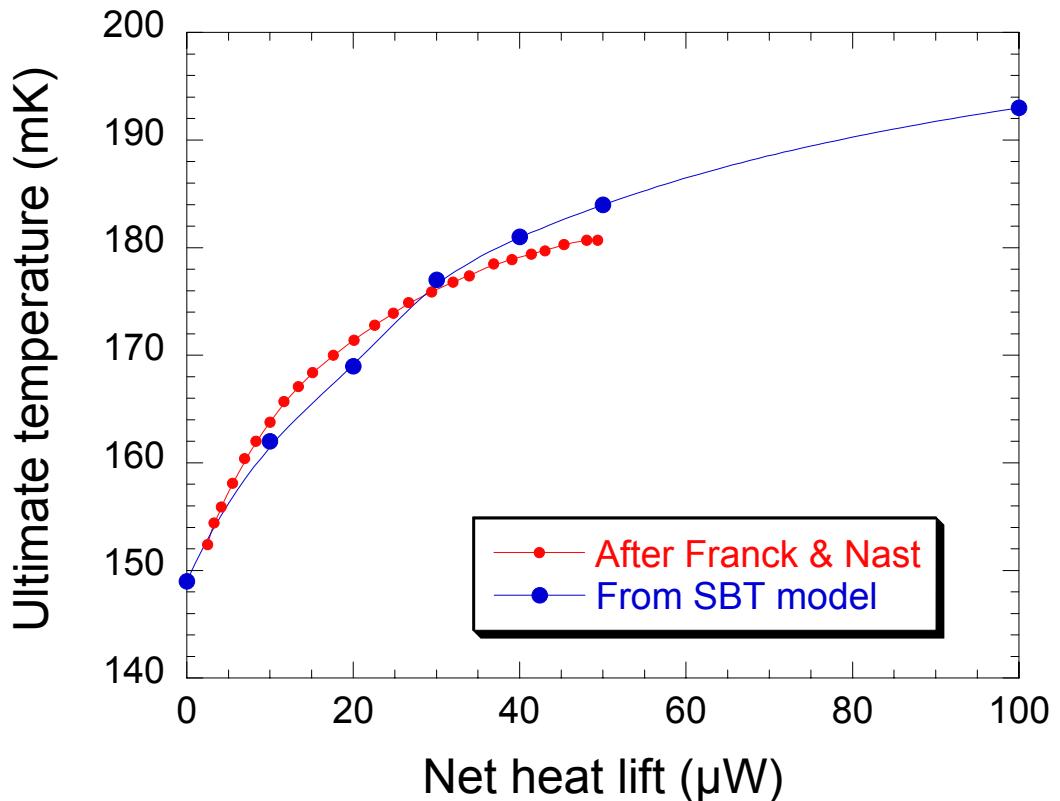


# SORPTION COOLER : SINGLE STAGE ULTIMATE TEMPERATURE ?

Open cycle : evaporator vented to space



*But need a valve !!*



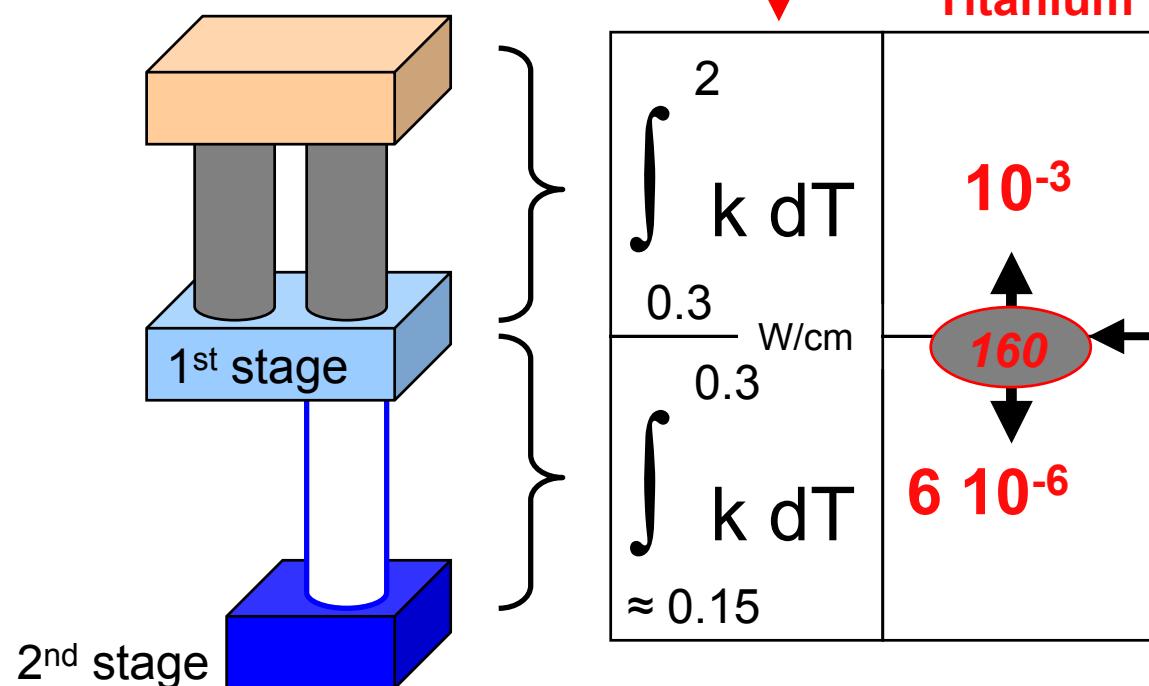
*(Neglecting Kapitza resistance)*

# DOUBLE STAGE SORPTION COOLER

$^3\text{He} / ^3\text{He}$

Mass flow rate :  $m =$

$$\frac{f_1(T) \cdot \varnothing^2}{L}$$



Pressure (bath)

$$P_{\text{bath}} = \frac{f_3(T) \cdot m \cdot L}{\varnothing^3}$$

$$P_{\text{bath}} = \frac{f_1(T) \cdot f_3(T)}{\varnothing}$$

Very ultimate  $\approx 170 \text{ mK}$

Other configurations

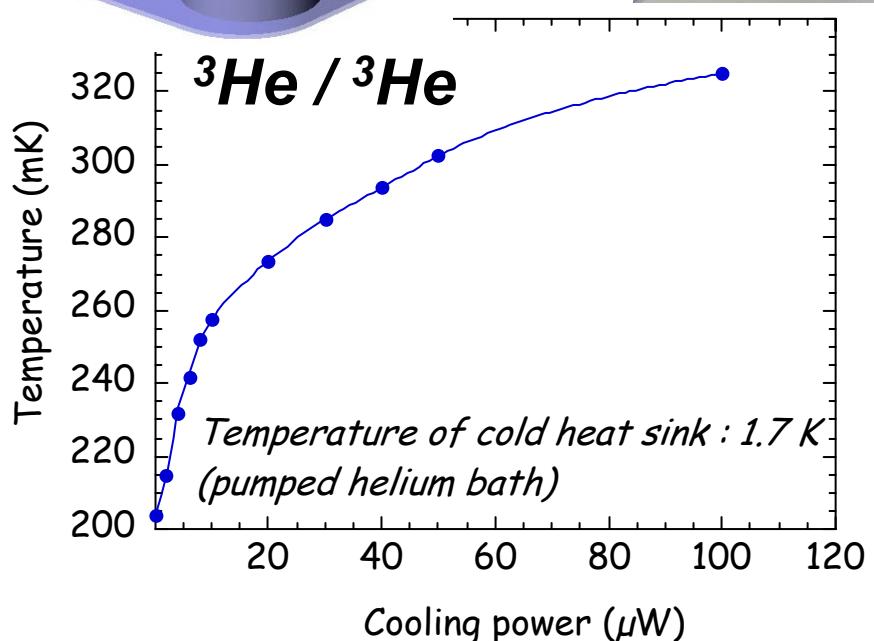
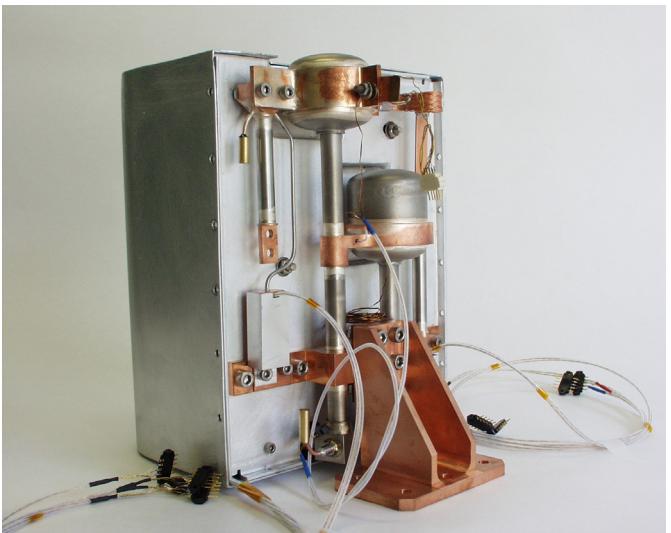
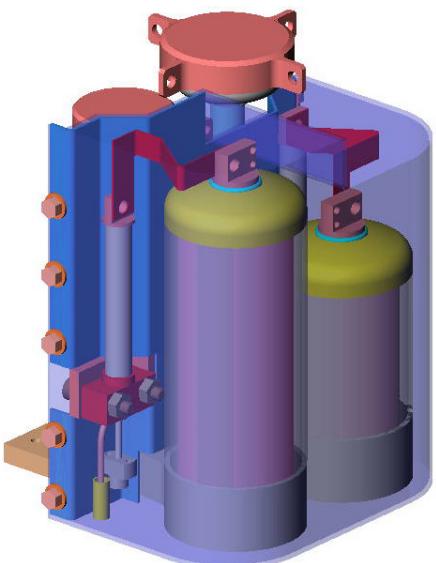
$^4\text{He} / ^3\text{He} :$

$4.8 \text{ K} - 260 \text{ mK}$

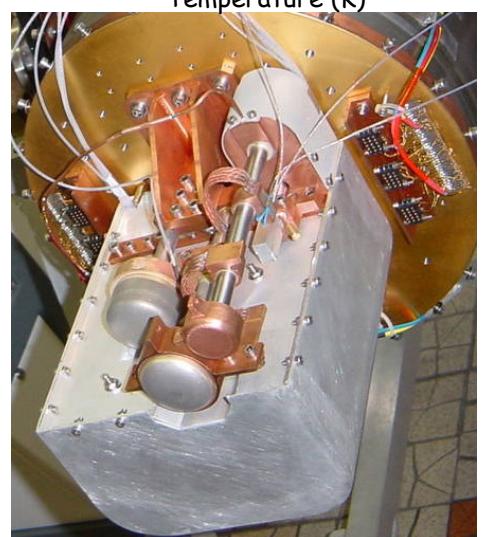
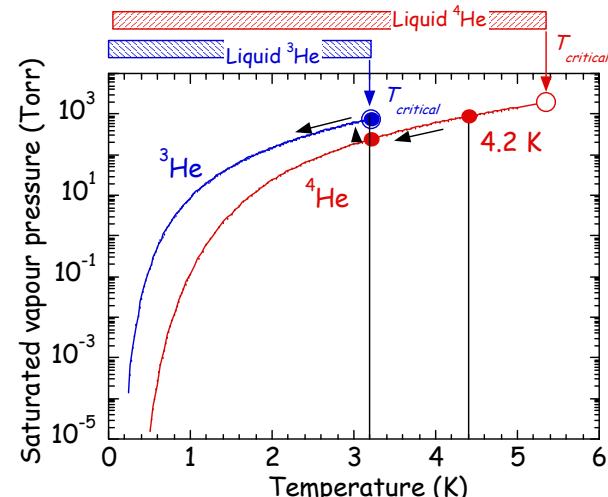
$^4\text{He} / ^3\text{He} / ^3\text{He} :$

$4.8 \text{ K} - 200 \text{ mK}$

# MULTISTAGE SORPTION COOLER



**$^4\text{He} / ^3\text{He}$**   
(32 / STP - 16 / STP)



**$^4\text{He} / ^3\text{He} / ^3\text{He}$**   
(32 / 16 / 2 / STP)



## XEUS

- X-Ray telescope in low earth orbit
- Detectors operate between 20-300mK

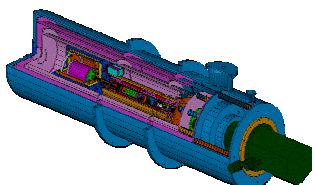


## DARWIN

- Interferometer to detect earth like planets
- Vibration free cooling of the detectors below 10K

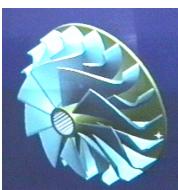
## CURRENT R&D ACTIVITIES

### 20-50mK ADR (MSSL)



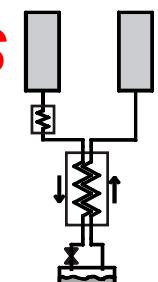
### Reverse Turbo Brayton cooler

Compressor development  
(50mW@ 4K) - Air Liquide

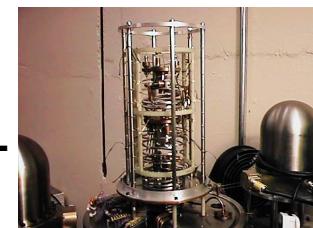


### 4K sorption cooler University Twente

Vibrationless cooler operating from 60K. 10mW at 4-5K



### 300mK sorption cooler with mechanical precooler RAL



## CURRENT NEEDS

- 40-80K, 1-10W single stage coolers for all applications
- 10-50K two stage coolers for precooling of low temperature coolers or detector cooling, Zero-Boil Off Hydrogen
- 4K coolers for Science applications with specific requirements (low vibrat., precooling of sub-K cooler)
- Small cooling systems for interplanetary missions, mini/micro satellites (medium lifetime)



**FI - Helsinki**  
Low T. Lab.



**SINIS Junction**



**SW - Gothenburg**  
Chalmers Univ.



**SINIS Junction**



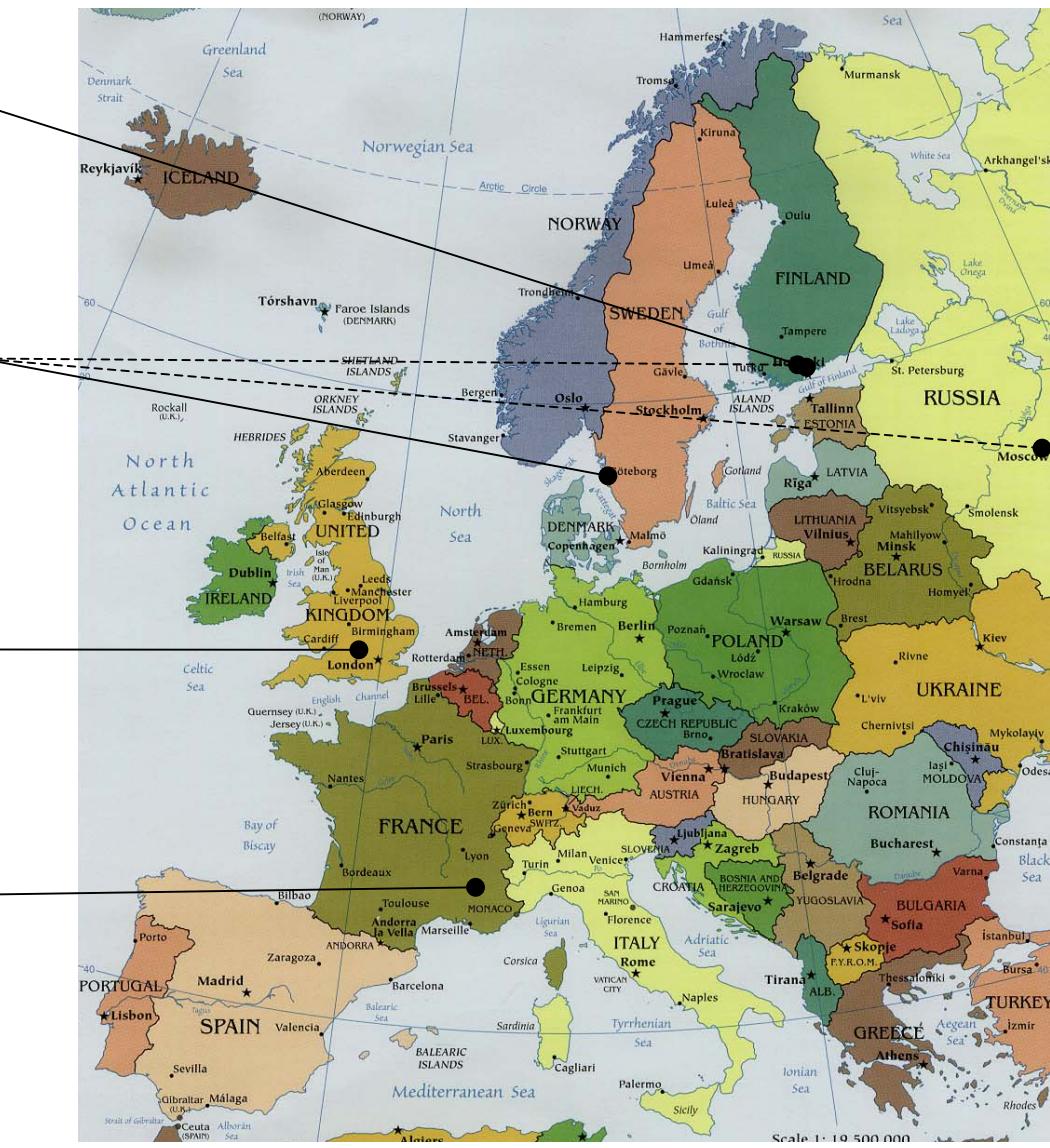
**UK - Chilton & Dorking**



**RAL : Helium JT loop**



**MSSL : dADR**



**FR - Grenoble**



Air Liquide + : Space dilution  
CRTBT (CNRS)



SBT (CEA) : Sorption Coolers  
+ Mini ADR



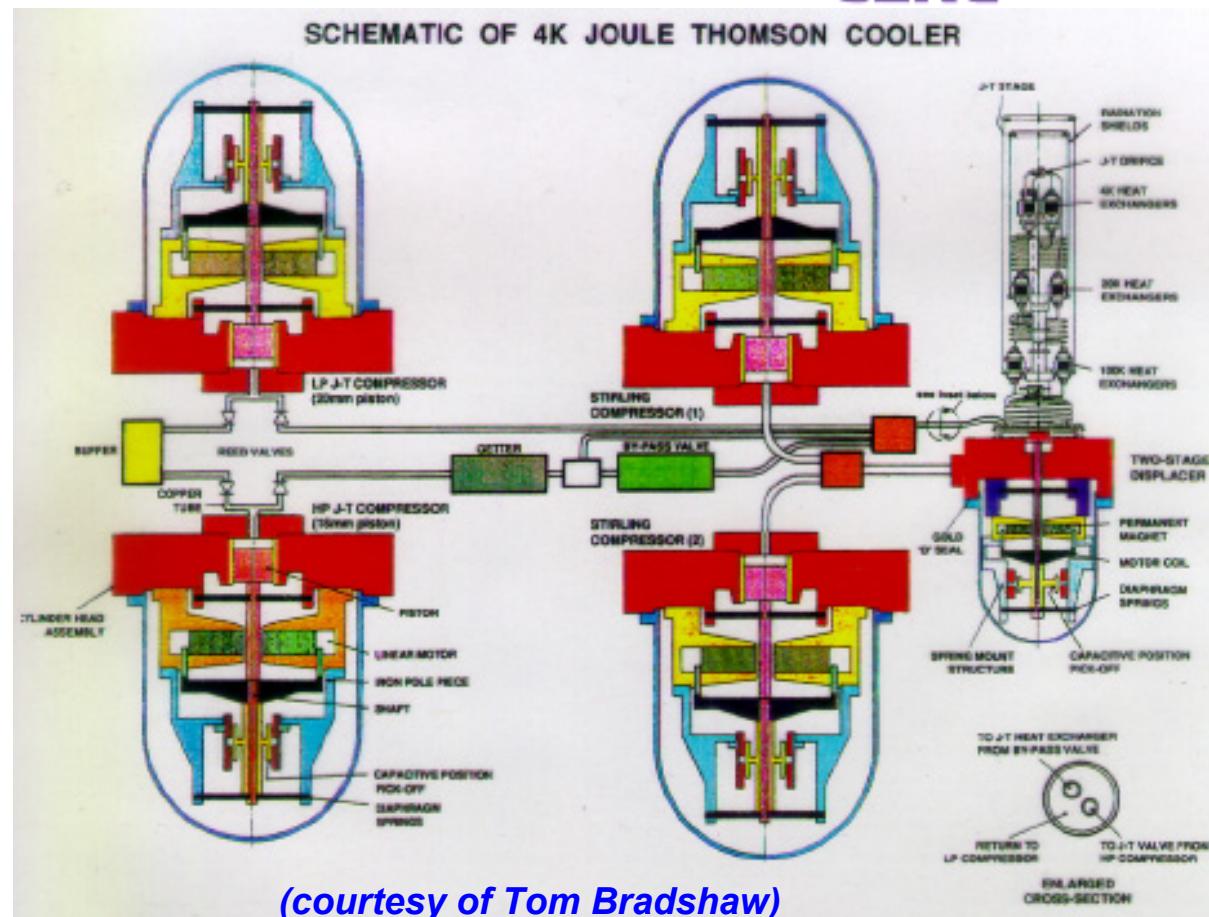
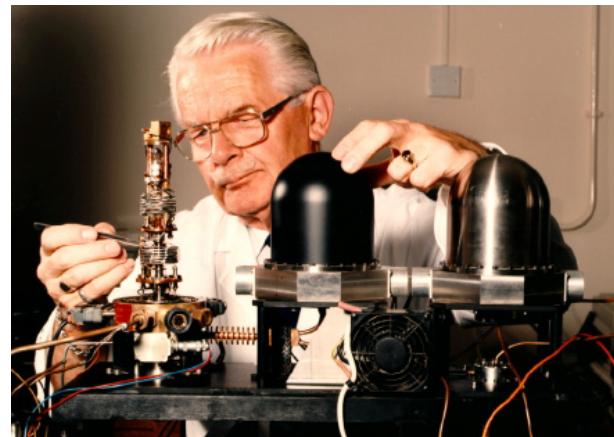
Typical performance :

10 mW @ 4.2 K with  $^4\text{He}$

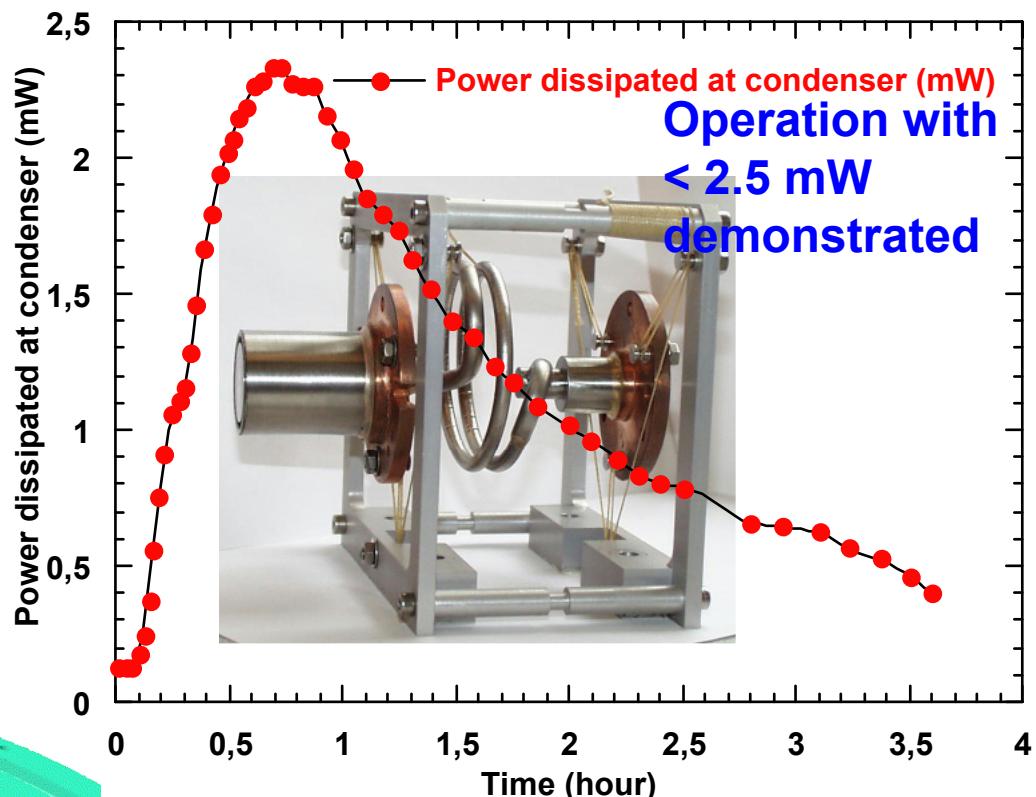
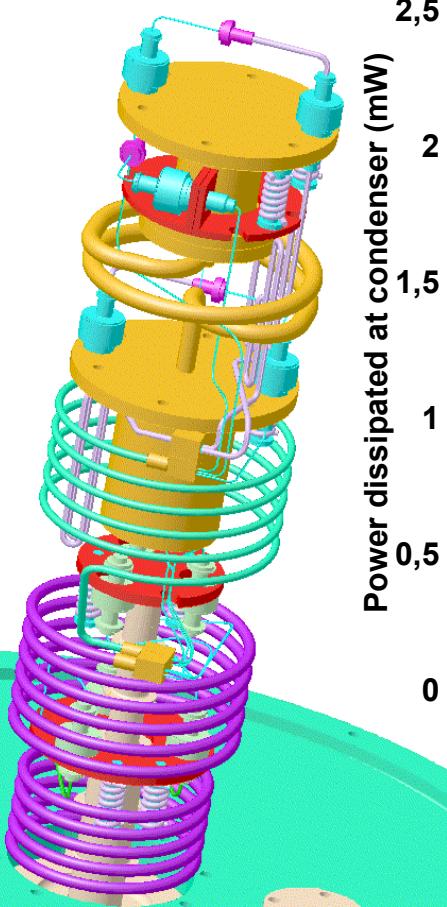
5 mW @ 2.5 K with  $^3\text{He}$



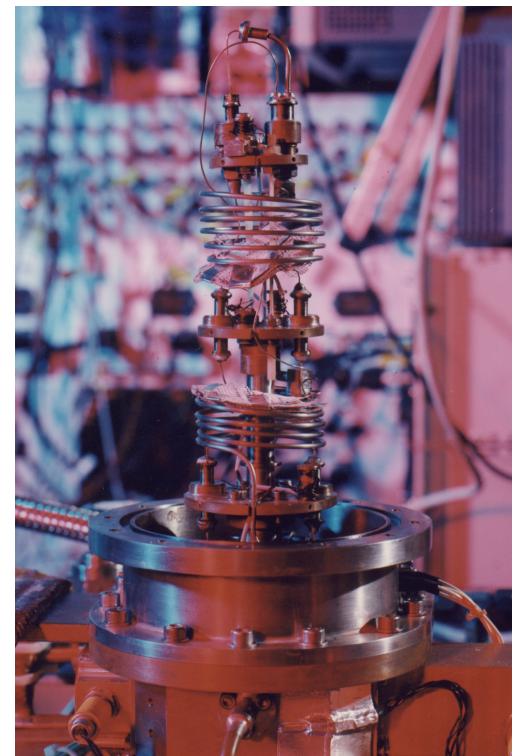
RAL  
ASTRIUM



**ESA CONTRACT (Collaboration ASTRIUM, RAL & CEA-SBT) : Association of a single stage  $^3\text{He}$  sorption cooler with a 2.5 K JT loop**



**Development still ongoing**



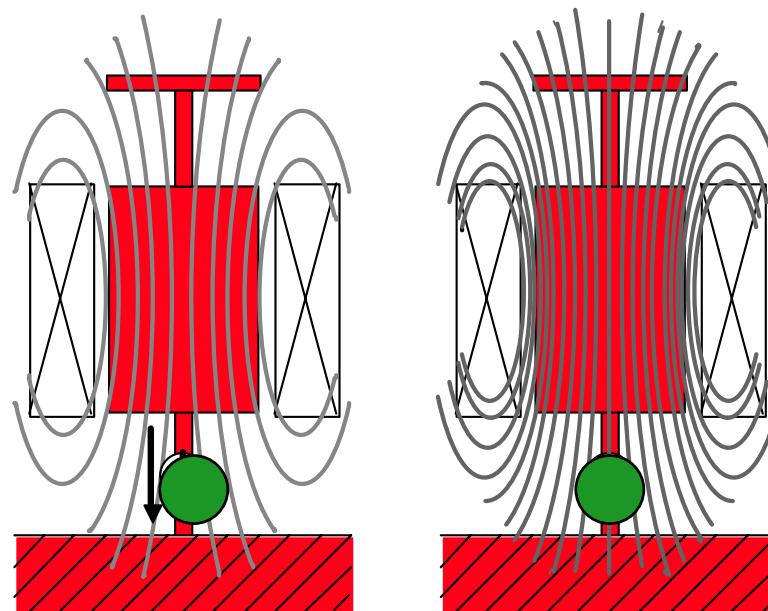
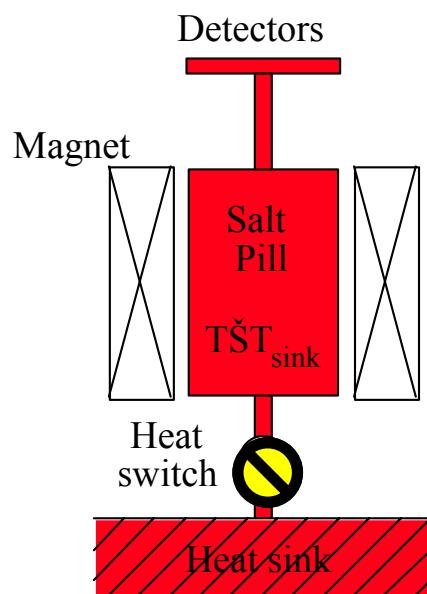
**Possible application for XEUS project**



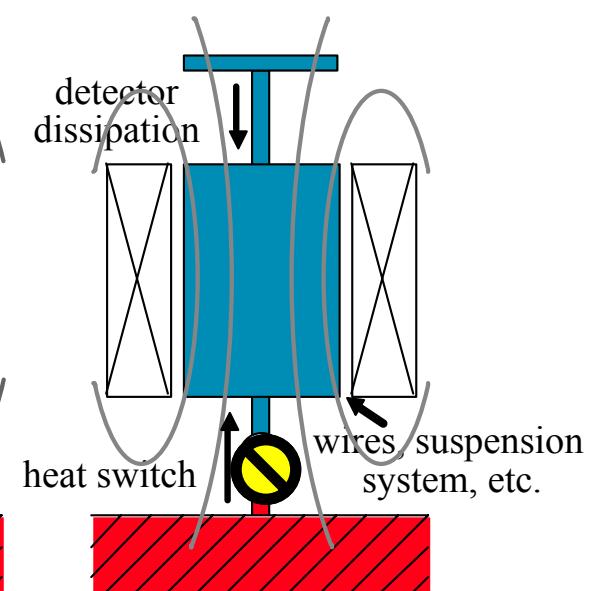
(courtesy of Tom Bradshaw)

Collection of paramagnetic ions :  
interaction energy  $\ll kT$

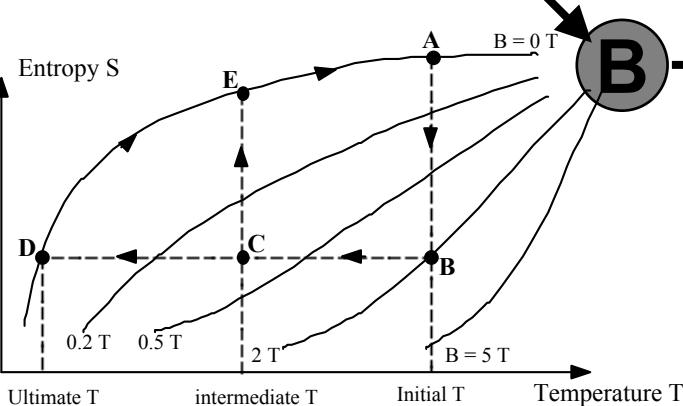
### Recycling



### Operational Mode



$$S_{H=0} > S_{H \neq 0}$$

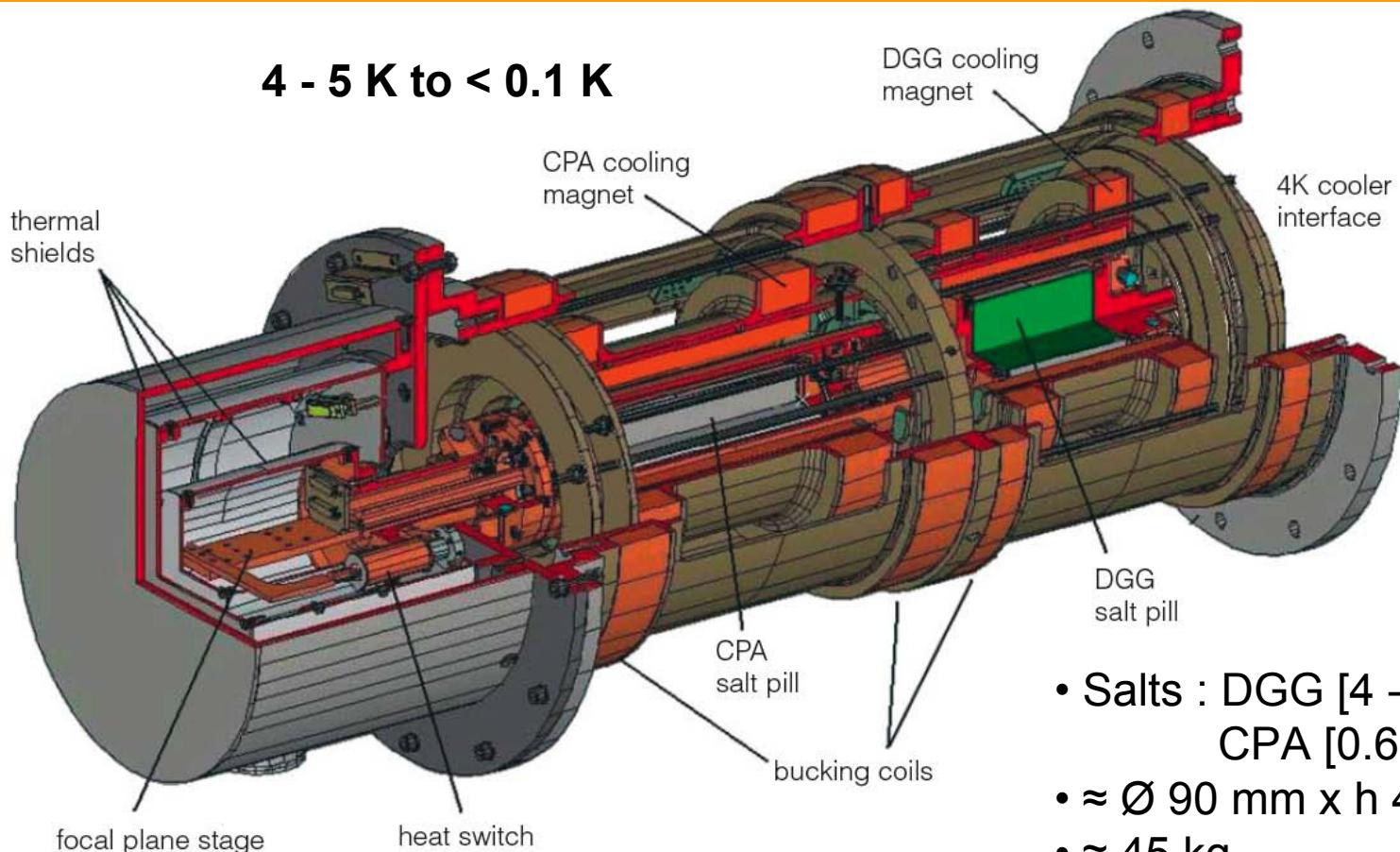


First proposed in 1926 by Debye  
First practical demonstration :  
(De Haas et al.) : 1933

**Wide range of  
temperature available  
down to few mK**

# DOUBLE ADR (dADR)

4 - 5 K to < 0.1 K

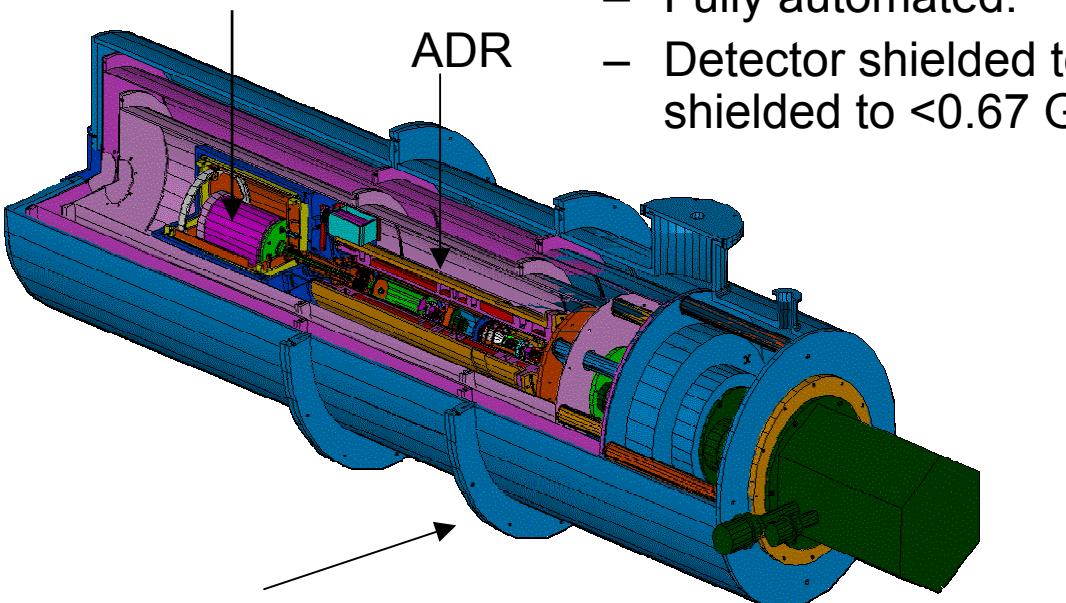


(courtesy of Ian Hepburn)

- Salts : DGG [4 - 0.6K] + CPA [0.6 - <0.1]
- $\approx \varnothing 90 \text{ mm} \times h 440 \text{ mm}$
- $\approx 45 \text{ kg}$
- $\approx 3 \text{ Tesla}$
- Operating T  $\approx 0.1 \text{ K}$  or less  
(target : 30 mK)



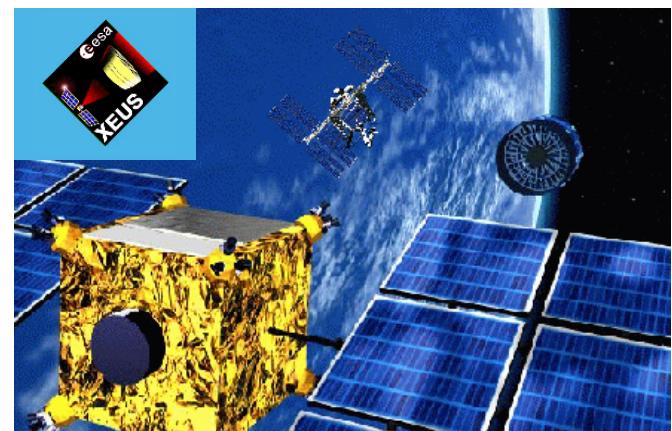
Magnetic shielded  
detector volume  
 $B < 0.05$  Gauss



Cryogen free cryostat  
(courtesy of Ian Hepburn)

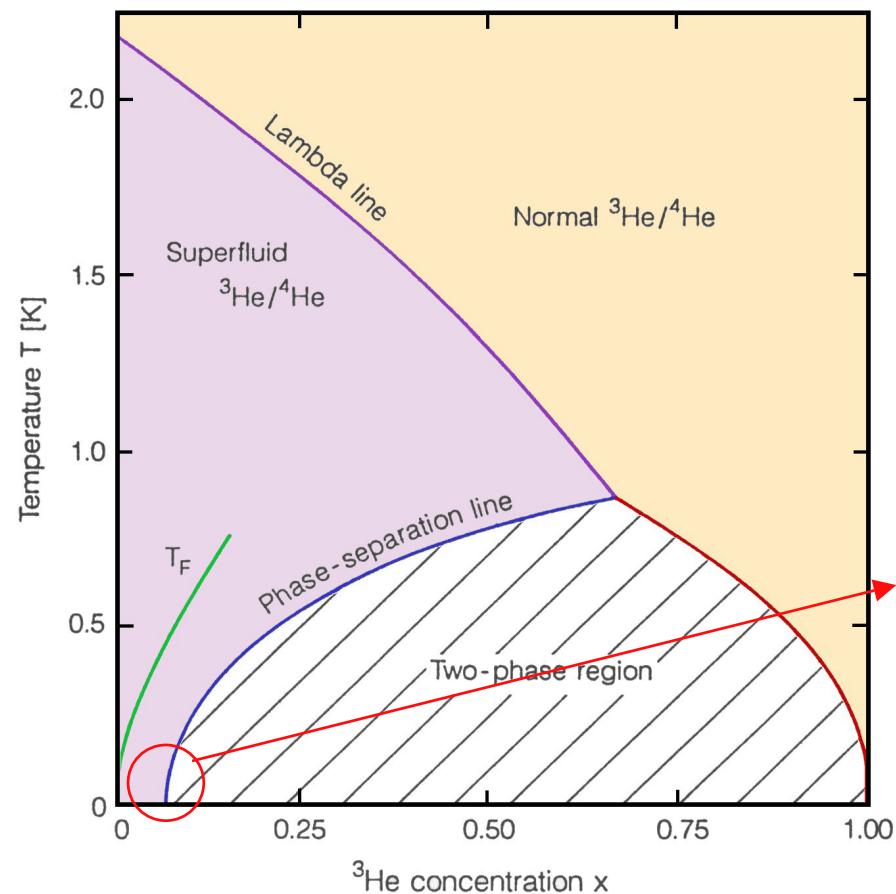
### Some main requirements.

- Cryogen free system (<5 mW peak heat load on cryocooler).
- < 30 mK base temperature.
- 24 hour hold time at 50 mK.
- < 4 hour recycle time.
- 4.5 K bath temperature
- Fully automated.
- Detector shielded to <0.05 Gauss (ADR at max field), system shielded to <0.67 Gauss (ADR at max field).



Possible application for XEUS project

## Peculiar behaviour of ${}^3\text{He}/{}^4\text{He}$ mixture

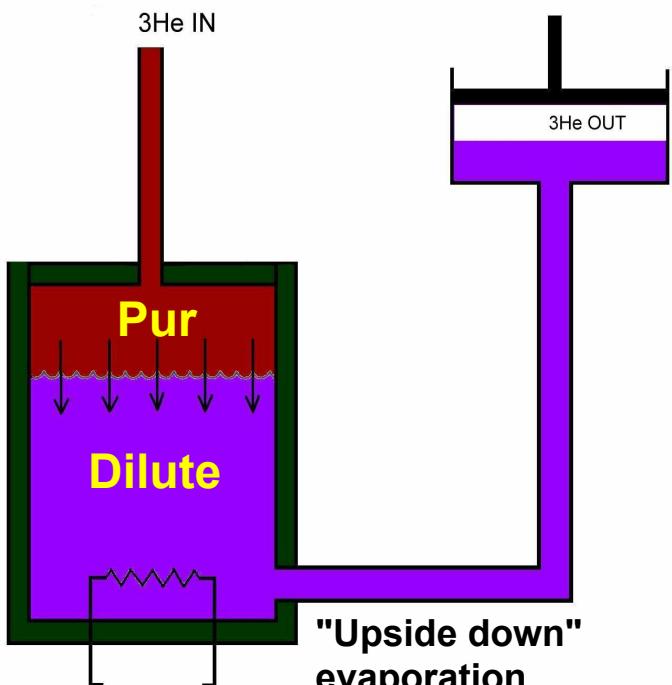


$$S_{\text{dilute } {}^3\text{He}} > S_{\text{pur } {}^3\text{He}}$$

"Flowing"  ${}^3\text{He}$  atoms from pur to dilute

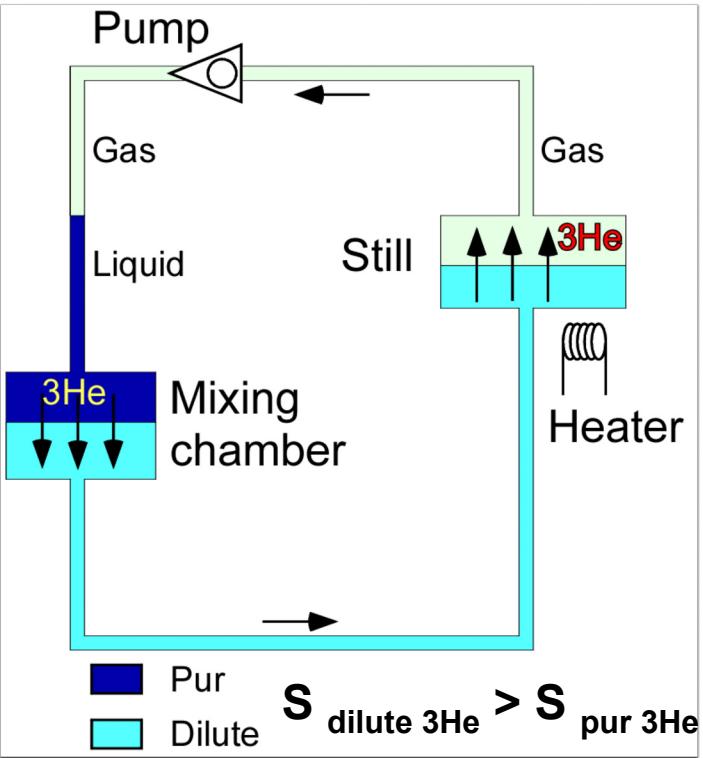
Cooling effect

Even at low  $T$   
6.4% of  ${}^3\text{He}$  in the mixture



First proposed in 1962 by London - First practical demonstration (Hall & Neganov) : 1966

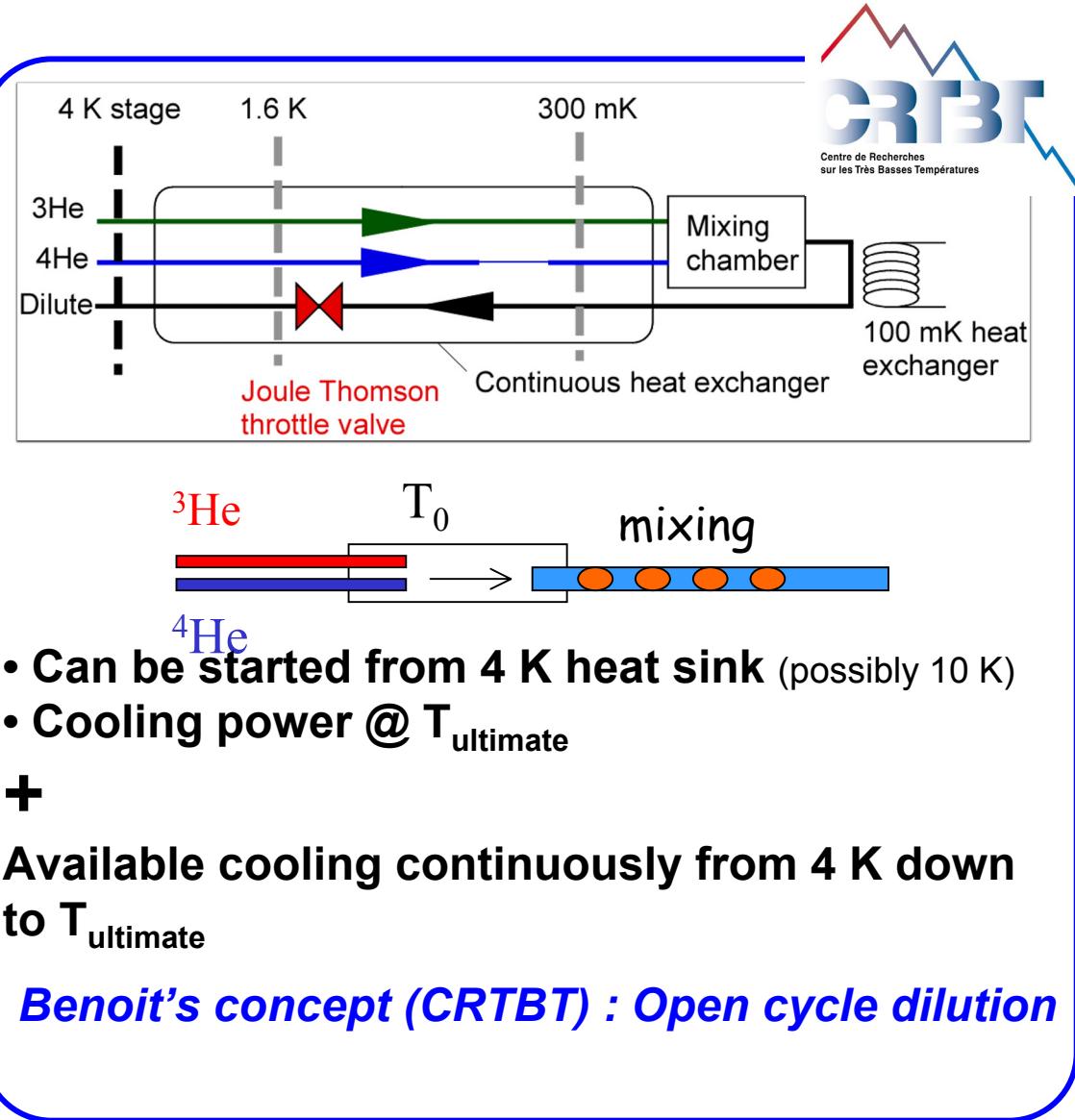
# DILUTION REFRIGERATOR ALTERNATIVE CONCEPT (SPACE)



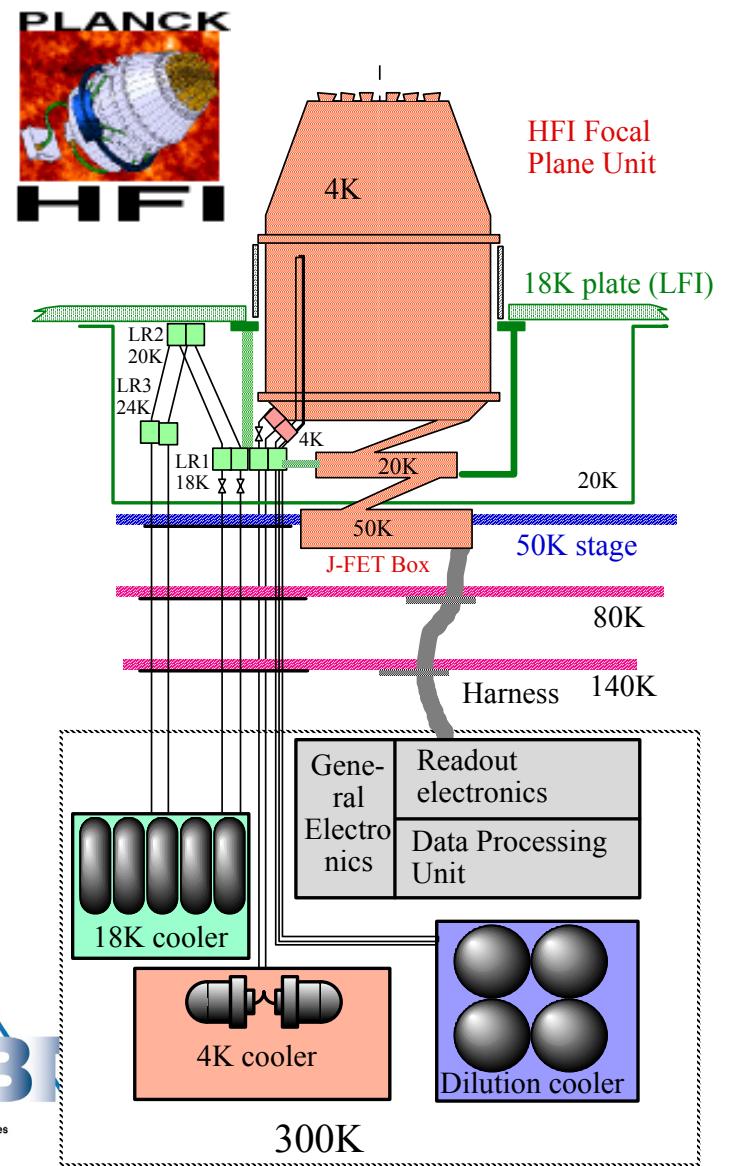
**Circulating concept**

**Phase separation**

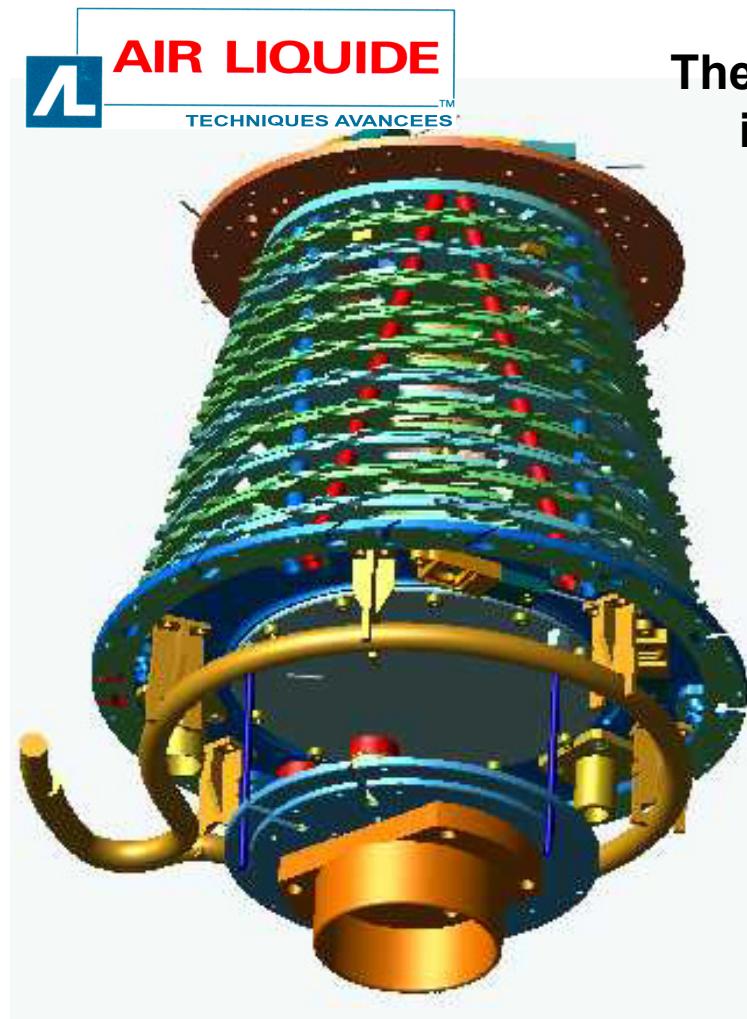
**Gravity dependent**



- **HFI cooling chain**
  - PLANCK PLM passive cooling down to 50K thanks to V-grooves
  - 18K sorption cooler: for cooling HFI and LFI
  - 4K mechanical cooler: required for cooling the HFI focal plane unit and the Dilution Cooler
  - 0.1K Dilution Cooler: required for cooling the 0.1K bolometer plate.
- **0.1K Dilution Cooler**
  - Models built by *AIR LIQUIDE DTA*:
    - A high fidelity mock-up
    - A qualifying model: CQM
    - A flight model: PFM
  - Process of an open circuitry dilution worked-out by CNRS-CRTBT and tested in real conditions with the Archeops balloon mission in winter 2002.
  - Process patented by CNES (n°93.08201)



# PLANCK DILUTION COOLER



The 3He / 4He dilution  
in open circuitry:



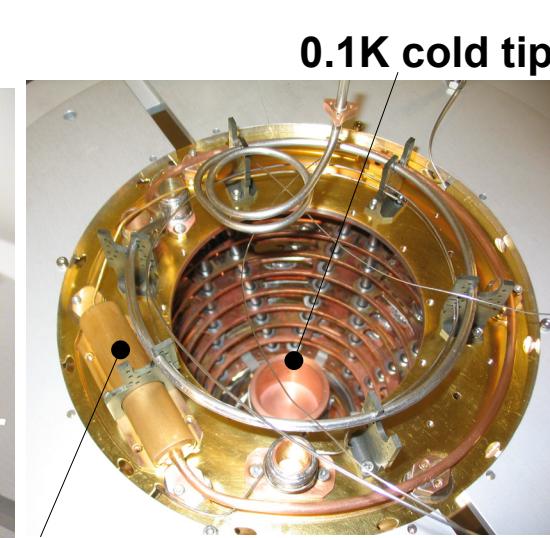
Mixing box



Counter flow heat-exchanger



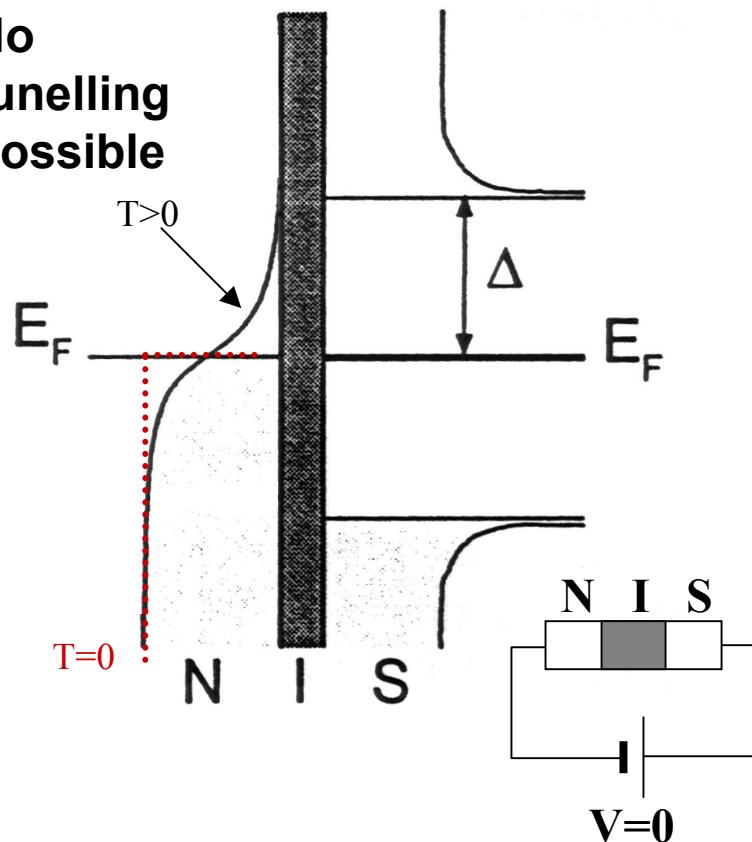
0.1K-1.6K counter-flow  
exchanger integration



0.1K cold tip  
1.6K JT expanding box

> 200 nW @ 100 mK achieved

No tunelling possible



Normal metal and superconducting material

Electronic densities

tunelling

$E_F$

$eV$

$\Delta$

$E_F$

N I S

N I S

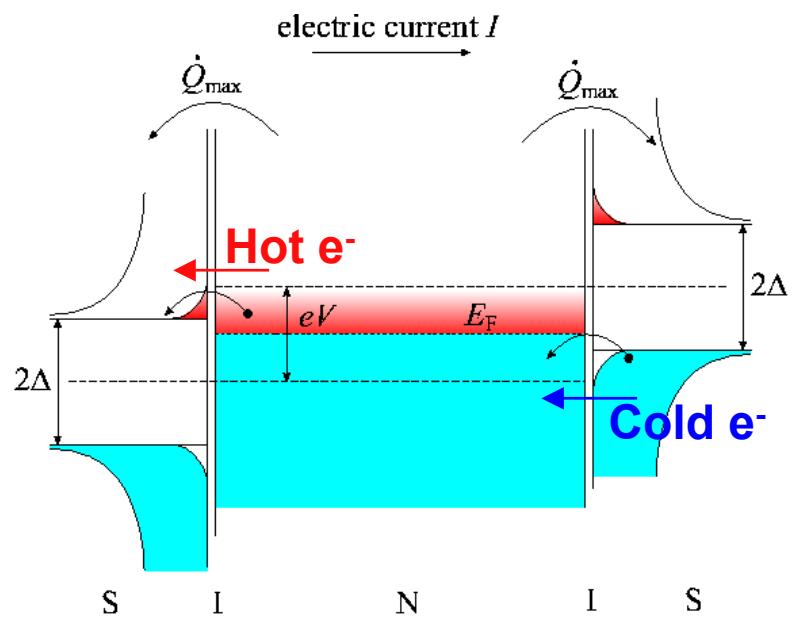
$V \neq 0$

Tension : Collecting of metal hot electrons.

First proposed in 1980 by Melton - First practical demonstration (Nahum) : 1994

# SINIS COOLER

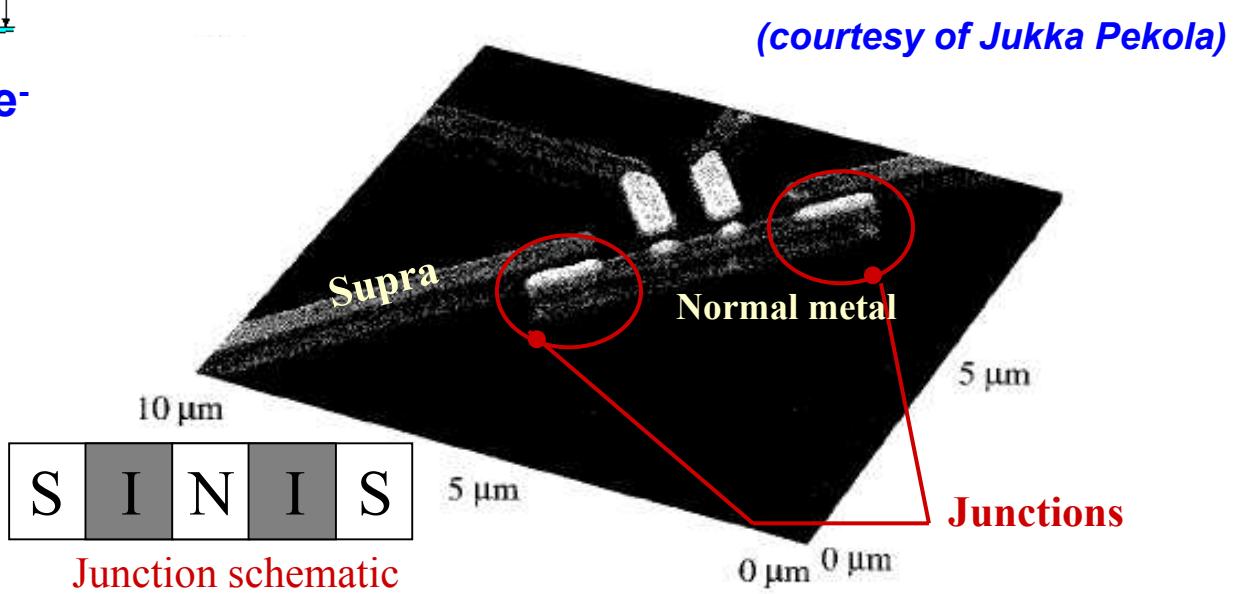
Take advantage of the symmetry  
**NIS → SINIS**



- (SI)NIS junction cooler:
  - Hot electrons removed from the normal metal
  - Normal metal electron temperature is reduced (*electronic cooling*)
  - Lattice temperature (in contact with the normal metal) is reduced (*Lattice cooling*)

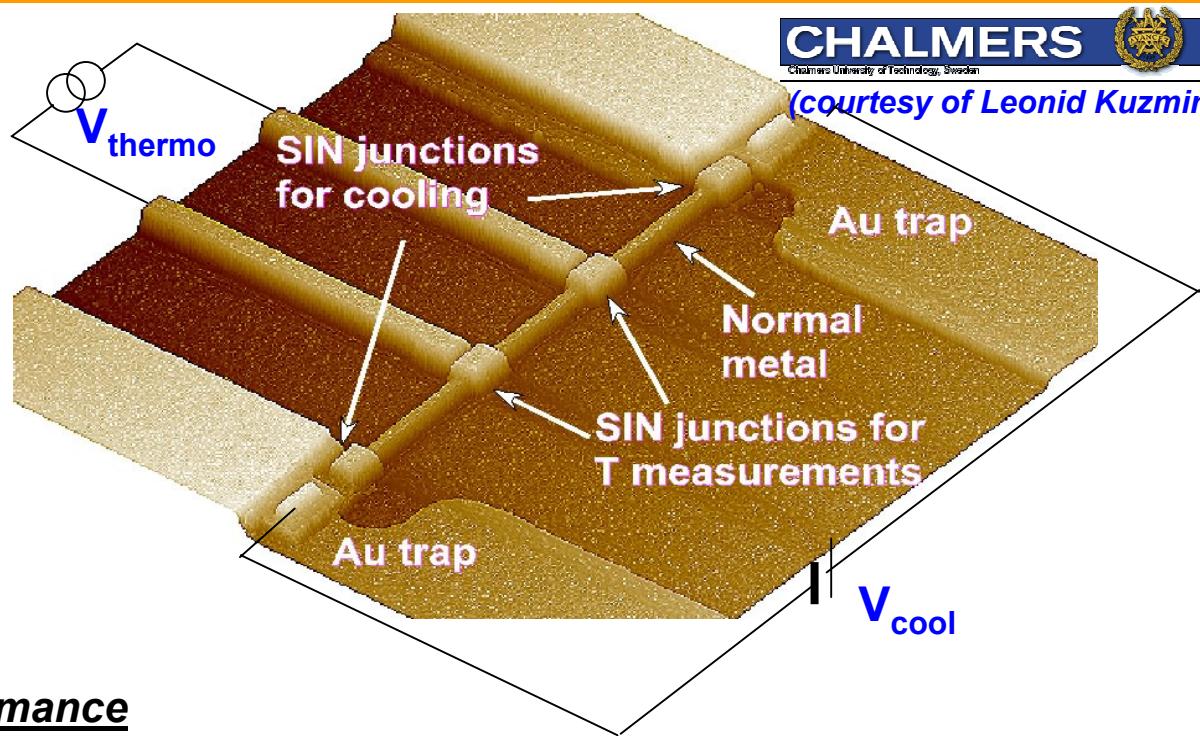
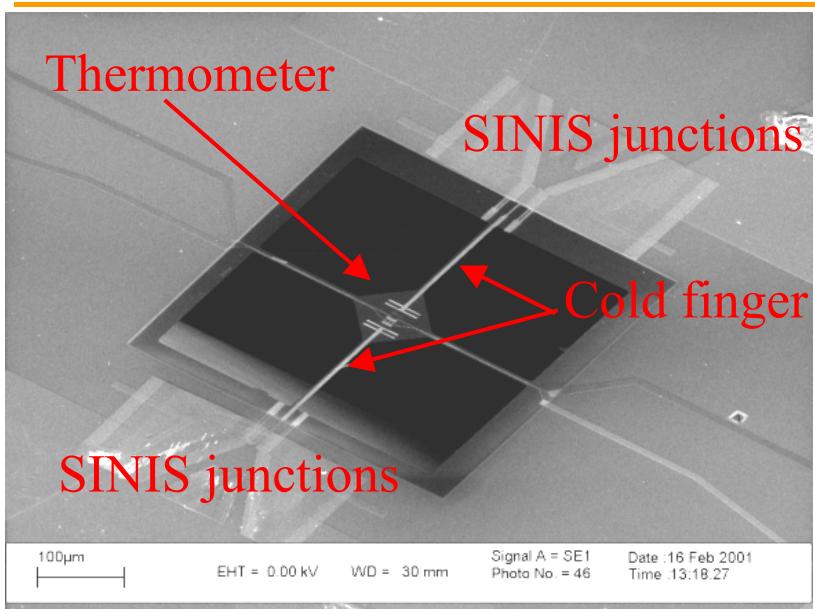


Helsinki University of Technology  
Low Temperature Laboratory



First proposed in 1980 by Melton  
First practical demonstration (Nahum) : 1994

# SINIS COOLER (HELSINKI LOW T LAB + CHALMERS UNIVERSITY)



Helsinki University of Technology  
Low Temperature Laboratory  
(courtesy of Jukka Pekola)

### Typical performance

- electron cooling from 300 mK down to 100 mK demonstrated
- "real" object (silicon nitride membrane) : 200 mK to 100 mK demonstrated

Cooling power of 1 junction : few pW  
Need many !

**Challenge : electron/phonon  
coupling at low temperature !**

Promising technique

If successfull could be used  
in XEUS mission

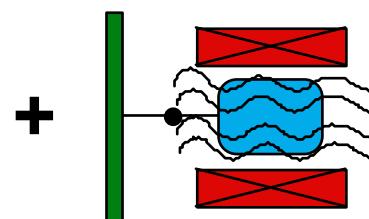
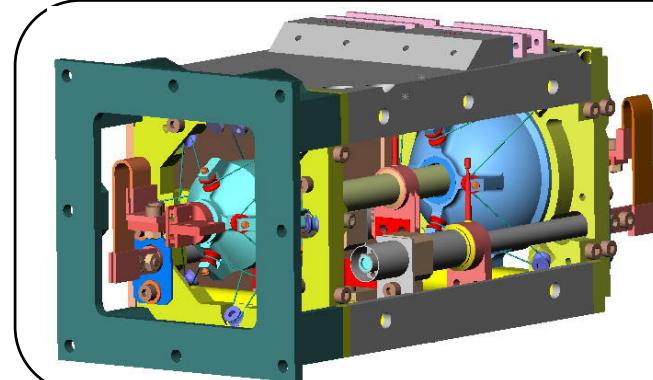
# SORPTION COOLER + ADR

**ADR**

**Colder stage  
requires  
lower fields**



- Lower stored energy
- Ease magnetic shielding
- Lower mass
- compactness
- Lower parasitic load from current leads

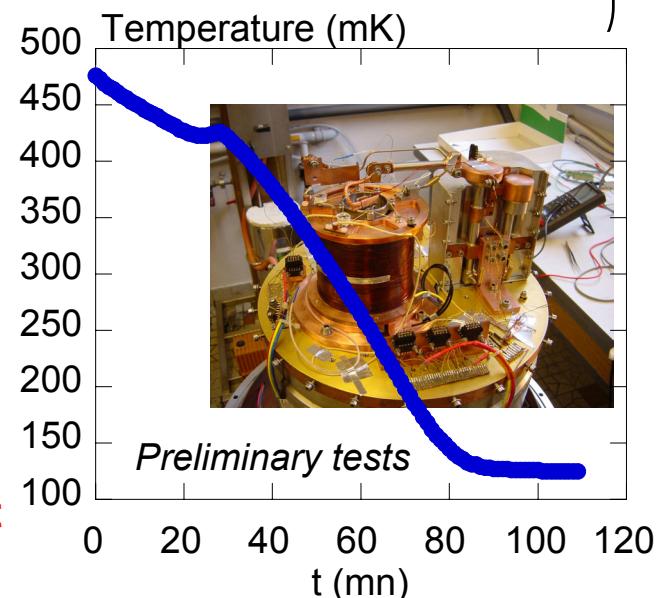


Miniature ADR  
coupled to single  
stage  ${}^3\text{He}$   
sorption cooler

**Lower  
temperature** *or* **Continuous  ${}^3\text{He}$   
sorption cooler**

- Preliminary numbers :
- Paramagnetic salt : CPA ( $89^\circ\text{C}$ )
  - Amount of salt  $\approx 100$  grams
  - Field required  $\approx 0.5$  T
  - Magnetization energy  $\approx 0.5$  J

→ **24 hours @ 100 mK  
With 2  $\mu\text{w}$  useful lift**



**VOILA,  
THANK YOU FOR YOUR ATTENTION**

**Merci**